Electromagnetic flyer plate technology and development of a novel current distribution sensor

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Electromagnetic Flyer Plate Technology
and Development of a Novel Current Distribution Sensor

A doctoral thesis

by

Kaashif A. M. Omar

(MPhys. Physics with Astrophysics,
University of Leicester, 2007)

Submitted in partial fulfilment of the requirements

for the award of the degree of

Doctor of Philosophy of Loughborough University

November 2014

To the School of Electronic, Electrical and Systems Engineering,
Loughborough University, Loughborough, UK

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Acknowledgements

With the grace and blessing of Allah (SWT), I have been able to complete this work, and I hope to continue in the pursuit of knowledge as is commanded by him…

Completing this research project and writing up this thesis has been full of ups and downs and it has been a very long journey, I can vaguely recall a young(er) single scientist who began this work not knowing where it would lead to; now, I am happily married to my wife Humna, having just celebrated our first wedding anniversary, and about to start the next big chapter in my life, which is to become a father…

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Thank you all
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Abstract

The main driver in conducting this research was to simulate the mechanical shockwave imparted to a target material by the deposition of cold x-rays. Simulating the mechanical effects of cold x-rays is of paramount importance when qualifying new and existing heat shield materials for survival in hostile environments.

During an exo-atmospheric nuclear detonation, the initial effects on any object will primarily be due to x-ray deposition in the target material. There are two broad categories into which the radiation can be classed; these are hot and cold x-rays, classified by their effects on the target material. Hot x-rays can penetrate deeper into a material and deposit energy in the interior, whilst cold x-rays deposit energy in only the outer few hundred microns of the material due to their lower penetrating energy.

In either case, when a large amount of energy is deposited a shockwave is generated in the material. Hot x-rays produce a thermo-mechanical shock wave within the target, whereas cold x-rays produce a shockwave which travels from the exposed side and into the material. This work is only concerned with the effects of the cold x-ray deposition. The process which generates the shockwave in the material is described below.

As cold x-rays are absorbed, a thin layer develops an increased internal energy density. The material rapidly vaporizes and is ejected normal to the surface (figure 1). This in turn sends a shockwave through the remaining material due to the conservation of momentum. The wave travels through the material until it reaches a boundary (such as the back surface) where it can cause significant damage to itself and other equipment due to the fracturing and ejecting spall.
Figure 1, Incoming cold x-rays depositing energy in thin outer layer (red layer), resulting in a shockwave (yellow) and associated damage at rear surface.

There are various different techniques and methods of simulating the effects of cold x-ray deposition but this thesis concentrates mainly on the pulsed power (electromagnetically driven methods) which can be utilised. After reviewing some of the methods the most promising technique was identified as the electromagnetic flyer-plate or “foil slap” technique.

Once the experimental platform was fully established, the research focussed on the development of a method of determining the current distribution across a wide transmission line. A sensor was developed, termed the MIDOT. This was a crucial feature of the work, as it provides a method of directly measuring the variations in the local current density. This is a feature which has not been achieved previously and is an area that will open up a range of research possibilities in the future.

The MIDOT sensor is described in detail together with the results from experimental shots carried out to demonstrate its performance. The majority of the work was performed at low voltage to validate the proof of principle. Methods to optimise the sensor for this particular application and for improving its sensitivity were also investigated. The further development of the current distribution sensor will form part of any follow on work initiated by this research.
Thesis summary

The work undertaken as part of this thesis covers a wide range of engineering and scientific research as is evident in the rest of the thesis. The initial aim of this work is to initially determine the most suitable accelerator technique applicable to simulating the mechanical effects of cold x-rays. This is achieved in chapter 1 by reviewing various techniques for accelerating the flyer and assessing its applicability to the work being undertaken.

Chapter 2 focuses on the development of 2 independent facilities; one of these was a university owned pre-existing facility which was completely refurbished using the design and under the technical supervision and guidance of the author. The second facility was a brand new high current system designed, built and commissioned by the author. The author was also responsible for the project management of this new facility to ensure it was built to time, cost and met all the necessary requirements.

In chapter 3 the experimental platform characteristics are assessed and the system component values are determined to allow a computer model to be developed and subsequently extended in chapters 4 and 5.

Chapter 4 is solely focused on determining the best way to control the current pulse. In this chapter the novel, use of a very large exploding foil to tailor current pulses of hundreds of kA is described in great detail. An alternative option of a non-destructive damper is also introduced and the validity of each of these methods is successfully demonstrated. The next stage of the model is the introduction of the flyer motion; this is incorporated into the model in chapter 5.

Chapter 5 fully describes the 1-dimensional motion of the flyer due to the modelled current pulse. The various assumptions and their justifications are also explained. The introduction of the motion of the flyer does add complexities to the electrical performance; however these effects are taken into account to further increase the accuracy of the model as shown in chapter 5.

Chapter 6 summarises of various standard diagnostics which have been used during the work. The chapters also introduces the most unique aspect of this research which is the development of a novel sensor with the capability of determining current
flowing within its vicinity without affecting the current flow in the circuit being measured. This inductive probe has been named the MIDOT and is a major accomplishment achieved by the author.

Chapter 7 covers all the preliminary experiments and the design and build stages prior to designing the initial sensor array. The results in chapter 7 also lead on to the initial set of high voltage tests on one of the high current capacitor banks which show that the sensor does indeed have the potential to become a very useful tool when it comes to designing flyer plate experiments.

Chapter 8 describes the development of a larger array comprising 50 sensors which can be simultaneously measured to obtain a “snapshot” of the current distribution during an electrical discharge. This chapter describes how the data from the array could be analysed to quickly obtain the qualitative current distribution as well as how the actual current values can be obtained from a well calibrated array.

Chapter 9 is a summary of the work completed and focusses on the novel aspects of the work such as the methods of damping the current as well as reviewing the performance of the MIDOT sensor.
CHAPTER 1

Background information and review of various electromagnetic accelerator techniques.

This chapter reviews the potential accelerator technologies and confirms that the flyer plate technique that is taken forward is the most suited to the work being undertaken. There are various different techniques for simulating the effects of cold x-ray deposition [1] but this thesis concentrates mainly on the pulsed power (specifically electromagnetically driven) methods which can be utilised. After reviewing some of these, the most promising technique was identified as the electromagnetic flyer-plate or “foil-slap” technique [2], with the technique being outlined in figure 1.1.

![Figure 1.1, Aluminium foil impact to replicate the effects shown in figure 1.](image)

Figure 1.1, Aluminium foil impact to replicate the effects shown in figure 1.

The main difficulty in simulating the effects of x-rays on a macroscopic scale is the difficulty in producing a simultaneous uniform impulse across a sufficiently large sample. For the purposes of this project the target samples being used are almost 100 cm$^2$ in area. The total area of the target material which can be subjected to a simultaneous uniform impulse from the foil-slap will be used as the main criteria for selecting the appropriate technology to take forward.

For the purposes of this research programme, two separate facilities were utilised. One (AMPERE at AWE) was fully designed, built and developed as part of the work detailed in the thesis and the other (QUATTRO at Loughborough University) was
fully refurbished and reconfigured to meet the requirement of the relevant experiments.

One of the outputs of this research was the development of a basic 1D model named Electro Magnetic Strip Line Accelerator Program (or EMSLAP) which can accurately predict the mechanical performance of the flyer plate and also the electrical performance of a foil fuse used to tailor the current pulse. The development and use of this code is described in chapters three and four.

The assembly of the experiment, including the initial gap between the flyer plate and the target greatly affects the outcome of the experiment. It also identifies the need for developing careful and accurate assembly procedures to ensure reliable and reproducible results. The various parameters and procedures involved are identified in the thesis.

Eventually, the technology identified as the most promising was the stripline accelerator and this has been developed further at both Loughborough University and AWE. A 1-dimensional (1D) computer model has been developed as part of the research and has been validated by comparison against an existing 2-dimensional (2D) filamentary model at Loughborough University as well as being compared to experimental data. In addition to the computer models, the development of a novel inductive sensor is another key output from this research programme. All the units used in the thesis are in standard SI form, unless otherwise stated.

Many different pulsed power arrangements can be used to accelerate flyer plates, and certainly the concept of electromagnetic propulsion is far from new; with the first working example being demonstrated in 1902 by Kristian Birkeland [3]. Birkeland realised that the main constraint to the further development of the electromagnetic gun was "the problem of finding an energy source that could deliver enough power within a fraction of a second." In the past few decades there has been substantial development in the field of electromagnetic (EM) propulsion due mainly to major advances in energy storage technology.

The majority of research in this field is for military applications and is concentrated on the development of various electromagnetic guns [4]. Development of assisted
aircraft launch systems on aircraft carriers has also been performed to replace the existing steam powered systems [5]. However, the development of EM accelerators is not limited to military applications; other areas of current research include the development of the magnetically levitated (MAGLEV) train system and the concept of launching small satellites into low earth orbit (LEO) [6].

After a comparison of the various techniques, the stripline geometry, which exploits the electromagnetic repulsion between two oppositely oriented current-carrying plates was deemed to be the most appropriate technology for this work. This is due both to its scalability and its historical use in similar experiments since the 1960s. In the 1980s trials were conducted at AWE by Bealing and Carpenter, with flyers having an area of up to 1.4 m² being accelerated [2]. The work undertaken here uses smaller flyers and much more sophisticated diagnostics to obtain better quality data. A comparison of the various techniques is given in the next section.

1.1 Rail gun

Rail guns are frequently portrayed as the ultimate weapon in many ‘sci-fi’ films. In principle, if the projectile could be accelerated indefinitely, it would be possible to accelerate it to the speed of light! In reality there are of course many physical constraints which limit the practical speed achievable. Speeds of a few km/s have been reported in what are commonly termed “hypervelocity” rail guns. The “projectiles” in these systems are usually very small foils and plates and are used for micro meteor impact studies [7].

A rail gun is formed when a current loop with one section made from a sliding armature is assembled between two fixed parallel rails (figure 1.2). An outwardly directed force is generated, pushing the armature along the length of the rails when a current flows through this arrangement. In a single loop system (which is the simplest case) very large currents are required to obtain significant acceleration; the consequent arcing and friction unfortunately also lead to substantial erosion problems.
The force accelerating the projectile (or armature) is known as the Lorentz force and arises from the interaction between the magnetic field present between the parallel rails and the current flowing through the armature. The force generated is between the components of the magnetic field and the current which are perpendicular to each other. Figure 1.2 shows how the conductor geometry ensures this force is maximised. This also implies that an equivalent force will also push the two parallel rails apart; this has to be taken into consideration when designing and constructing such a device to ensure that it can withstand the transverse forces.

The magnetic field generated by a current carrying wire can be calculated using the Biot-Savart Law, However to illustrate the principle of the rail gun only the directions of the fields produced need to be considered. If the rails are regarded as having a circular cross section of minimal area (i.e. a very thin wire) the magnetic field generated will be in the form of concentric circles and in a direction given by the right-hand (screw) rule as shown in figure 1.2(b). Using Fleming’s left hand (motor) rule, the direction of motion can then be determined.

The above section provides a very basic introduction to railgun systems. In the years since its inception there have been many modifications to the basic arrangement to improve both the performance and the efficiency of the system. The majority of these increase the magnetic field in the space between the rails. Some of the modifications which have been applied to the basic design can be found in the paper by Henry Kolm, et al, [8].

Figure 1.2(a) - Orientation of the magnetic fields generated by currents flowing through the parallel rails. 1.2(b) - Cross sectional view of the same rails.
Features suggested include the provision of an auxiliary set of conductors to create a stronger magnetic field between the rails and having a pre-existing field before the breach of the gun to improve initial acceleration. Other systems of “launching” the projectile into the gun have also been proposed.

1.1.1 Limitations of the rail gun

As mentioned above, operation of a rail gun requires a very large current to be driven through the rails for the duration of the accelerating phase, which initially was one of the major hurdles to making this technology feasible. Only within the last 30 years, with the development of high energy density capacitors and other energy storage techniques such as flywheels and homopolar generators [9], as well as flux compression generators [10], has this technology become a viable option.

The description of the technology so far has been based on the assumption that the projectile is the armature. In reality the armature does not necessarily need to be the projectile, as it can also act as a sabot for the intended projectile. The armature does not need to be a solid object; a plasma armature can also be used [11] to provide the required conduction path. In such cases the design of the rail gun needs to have the additional components required to create an airtight ‘barrel’ and the projectile would need to be a tight fit to ensure the plasma does not move past it. The design would be analogous to the barrel of a conventional gun. The benefit of this option is that the wear on the rails can be dramatically reduced. If a solid armature is used, the surface area in contact with the rails needs to be maximised, to allow for efficient current transfer and to minimize the current density of any arcs that are generated, this reduces the erosion of the rails caused by the arcing.

One of the major issues with solid armatures is the effect of ‘gouging’. Two surfaces sliding past each other at high velocity suffer severe surface damage in the form of pits or gouges. The gouges are usually tear-drop shaped, with the pointed end facing upstream. Gouging damage has been experienced in rocket sled tracks and two-stage gun barrels as well as on rail guns [12].

Ideally it is desirable to eliminate the effect of gouging completely, although this is never possible especially with solid armatures. To alleviate the problem, rail gun systems are usually designed using materials which cause preferential damage to
the armature rather than the rails, as this is only used once. For this purpose, the rails are made as hard as practically possible and the armature as soft as possible. Development of this technology is an active area of research, with graphite being investigated as a material for suitable armatures [13].

It is difficult to overcome the static friction at the breach end of a rail gun and it sometimes happens that the armature becomes welded to the rails, leading to severe damage and a loss of effective acceleration time. One method of reducing this problem is by introducing the armature to the breach of the gun with an already appreciable velocity. The electromagnetic forces then further accelerate the armature as long as current is flowing through the system. Other factors such as having a strong uniform magnetic field already established at the breach prior to the armature being introduced will help provide better acceleration when the current begins to flow.

1.1.2 Rail Gun theory

There are numerous theories which explain the motion of projectiles in a rail gun. However, in its simplest form it is the Lorentz force which causes the armature to accelerate. This force is given by:

$$F = qE + q(v \times B)$$  \hspace{4cm} (1.1)

which gives the force experienced by a charged particle, moving through an electromagnetic field; where $E$ is the electric field intensity $B$ is the magnetic field intensity $q$ is the charge on the particle (typically the charge on an electron in the simplest case) and $v$ is the velocity of the charged particle. For the present case it is only necessary to consider the second term in equation (1.1), which determines the electromagnetic forces acting on moving charges in a magnetic field. In a rail gun the moving charge equates to the current ($i$) flowing through the armature, and as current is the flow of charge per second, the current through the armature length, $I$, is equivalent to charge moving at a given velocity; in other words $qv$ can be replaced with $il$.

Replacing the $qv$ term with $il$ in equation (1.1), where $l$ is the length of the armature in the direction of the current flow, gives
\[ F = q(\mathbf{v} \times \mathbf{B}) = i(l \times \mathbf{B}) \]  

(1.2)

This can be further simplified by taking the cross product and assuming that the magnetic field created is perpendicular to the current flow. This reduces equation (1.2) to the very familiar form:

\[ F = B i l \]  

(1.3)

The magnetic field can be calculated using the Biot-Savart Law (which for simplicity assumes the magnetic field to be produced by infinitely long rails of negligible cross section). The force on the projectile is then dependent on the current and the length of the rails alone. Although the assumption of infinitely long rails may not be realistic, it still provides useful information. Other approximations to the magnetic fields generated can be found in many text books.

It is also possible to calculate the forces using the principle of virtual work which can easily be found in the literature [14]. This provides a much simpler method of calculating the force using equation (1.4), sometimes referred to as the gun equation:

\[ F = \frac{1}{2} i^2 \frac{dl}{dx}, \]  

(1.4)

where \( \frac{dl}{dx} \) is the inductance gradient of the rail gun system in the direction of motion.

The theory behind this approach is that for any system the force exerted is equal to the potential energy gradient. For a rail gun the potential energy is the energy stored in the inductance of the system. Assuming a fixed resistance and a constant inductance per unit length along the entire gun barrel, equation (1.4) demonstrates that the instantaneous force on the armature is proportional to the square of the current flowing.

1.1.3 Applicability to foil-slap experiments

For the present foil-slap experiments, neither hyper-velocities nor extremely massive projectiles need to be utilised; the requirement is to deliver a uniform impulse over a comparatively large surface to simulate the effects of uniform x-ray deposition. Using this technique for the foil-slap experiments would mean the armature would be
the impactor and would need to be fairly thin. The large currents necessary and the prolonged acceleration period required would certainly vaporise the flyer long before it impacted the target, thereby making this technology unsuitable for the present project.

1.2 Coil Gun

Coil guns are not as widely utilised as rail guns but they are nonetheless a technology which could be a candidate to accelerate metallic objects to large velocities over a short distance. There are two main classes of coil guns - the, reluctance gun and the induction coil gun.

1.2.1 Reluctance Gun Overview

In essence, a reluctance gun is a solenoid which accelerates a ferromagnetic projectile by the magnetic field generated during excitation of the solenoid. Figure 1.3 shows a simplified schematic of such an accelerator prior to a current flowing in the solenoid. Figure 1.4 shows the effect a pulsed current has on the projectile. When the current is pulsed, the solenoid creates a nearly uniform axially directed magnetic field along its axis and it is this magnetic field that attracts the projectile. With accurate timing of the end of the current pulse the projectile can exit the solenoid with a considerable gain in kinetic energy.

![Schematic of a simple reluctance coil gun, initial configuration, no current flowing.](image)

Figure 1.3, Schematic of a simple reluctance coil gun, initial configuration, no current flowing.

Figure 1.4 shows how the projectile is accelerated during the current pulse.
Figure 1.4 Reluctance coil gun with a pulsed current flowing in solenoid, the projectile is accelerated towards the centre of the solenoid.

Figure 1.5 shows the cross-section of a reluctance gun. It also indicates the magnetic field produced by the coil and highlights the induced magnetisation in the projectile.

Figure 1.5, Schematic showing the principle behind the operation of a reluctance gun.

The magnetic field generated by the coil magnetises the projectile in such a way that it ‘sees’ an opposite magnetic pole, and is drawn towards the centre of the solenoid. If the current continues to flow after the projectile passes the midpoint, it will slow the projectile down as the magnetic field of the solenoid is oriented such that the projectile is drawn towards the centre of the coil; this is sometimes referred to as suckback [15].

The usual way to obtain an effective system for higher velocities is to use a series of coils which are activated sequentially as the projectile passes through them. This multistage system provides a continuous acceleration analogous to that of the rail gun, but has the added complication of requiring accurately timed current pulses.
Figure 1.3 outlined the basic components required for this type of accelerator. The barrel is made of a non-conducting material, as a metallic tube would interact with the magnetised projectile and the effect of eddy current braking would slow down the projectile. This effect can be seen by dropping a permanent magnet down a conducting, non-magnetic tube (such as copper or aluminium). As the magnet accelerates under gravity, the induced current in the tube increases; thus increasing the induced magnetic field in the tube that opposes the field of the magnet and causes the magnet to slow down. The net result is that an average velocity, lower than if it were falling under the force of gravity alone, is sustained as the magnet falls.

1.2.2 Induction Gun Overview

Although the assembly of this system is much the same as that of the reluctance gun, the acceleration in this case is caused by repulsion between the projectile and the magnetic field established by the coils, as opposed to the magnetic attraction exploited in the reluctance gun. The projectile is repelled out of the solenoid due to eddy currents induced in the projectile itself. The armature in an induction coil gun (figure 1.6) is not made from ferromagnetic materials, and normally either aluminium or copper armatures are used. A ring or tube can also be used for the armature, as eddy currents are only induced in the thin outer layer, leading to efficiency and performance advantages over a solid projectile. Other additions such as the use of an inner mandrel to guide the projectile can be adopted and the mandrel can also be rifled to improve the accuracy of the projectile by imparting spin to it. This configuration has been termed the theta gun [16].
Figure 1.6, Set up of an Inductance gun, the projectile is placed slightly off centre initially to ensure the projectile feels a net force.

The eddy currents induced in the projectile of figure 1.6 generate a magnetic field which interacts with the field of the solenoid. As the currents in the coil and the armature/projectile are in opposite directions the fields generated are also in opposite directions and as such will lead to magnetic repulsion.

As with the rail gun, the principle of virtual work can be applied to the system to provide a simple equation for calculating the force experienced by the armature; this is obtained by expressing the change in potential energy of the system as the armature moves through the coil. The potential energy in the induction coil gun is from the inductance of the solenoid coil. An expression to determine the force similar to that used for the rail gun is available [17]:

$$ F = \frac{i_1 i_2}{z} \frac{dM}{dx} $$ (1.5)

The two currents in this case are the primary current in the solenoid ($i_1$) and the induced currents in the coil ($i_2$). The mutual inductance gradient needs only to be taken in the direction of motion which in this case is the $x$ axis.
1.2.3 Applicability of coil guns (reluctance and induction) to foil-slap experiments

Foil-slap system requires a thin, flat projectile to be accelerated and the coil gun launchers outlined here are unsuitable for this purpose. There is the added complication of requiring additional and very accurate timing systems to ensure that continuous acceleration of the armature/projectile is maintained.

1.3 Induction plate launcher

An alternative to the coil gun is the induction plate launcher [18], which can accelerate flyers with much larger surface areas. It has been used for accelerating plates to intercept incoming projectiles, for use in active armour systems for tanks and personnel carriers [19]. Its major benefit is that it requires only a single stage of acceleration and there are no complicated timing issues involved. The drawbacks are that very high current pulses are necessary to induce the required current in the projectile, plus the lack of current shaping could lead to excessive capacitor damage yielding a very short life of the facility. The current flowing in the primary flat coil (sometimes called a pancake coil) induces eddy currents in a nearby metal plate; which interact with the primary current leading to EM repulsion. Induction launchers have been used to launch projectiles with greater surface area than can be achieved with rail gun systems [20].

Due to the nature of this technology it is inherently highly inductive. The induced current and therefore the EM force are proportional to the rate of change of current in the primary coil. A system based on this technique will require much more development before its possible use in the present controlled experiments.

1.3.1 Applicability of induction plate launcher to foil-slap experiments

The induction plate launcher appears to be a very good candidate for foil-slap experiments, however as stated in section 1.3 there is still a large amount of work necessary to obtain sufficient understanding of the technique to effectively use it to deliver specifically controlled impulses. An added complication would also be the requirement to produce uniform acceleration across the whole plate, given the
inherent non-uniform distribution of high frequency induced currents, to ensure the correct simultaneous impulse across the entire sample.

For these reasons the inductive launcher has not been taken forward as part of this research, although it may be used in future iterations of this technology.

1.4 Strip line Accelerator

This technology is employed at a number of high profile establishments where experiments such as those for determining the equation of state (EOS) of materials and for conducting isentropic compression experiments (ICE) are carried out. It should be noted that the flyer can either be a separate section which completely detaches from the transmission line or it can be formed of a thinner section of a continuous stripline as is show in in figure 1.7. Facilities such as the Z machine at Sandia and elsewhere at other US Labs and various university research labs across the world utilise this technique. In the case of EOS and ICE experiments, relatively small samples [21] are tested with flyers of surface area in the order of a few mm² being used. A typical stripline/flyer arrangement is shown below (figure 1.7); which is a typical setup such as is used on the Z facility.

Figure 1.7. Illustration showing the stripline setup as used in the ‘Z’ accelerator. The two configurations are with the target attached or held away from the flyer plate.

The two configurations shown in figure 1.7 are analogous to the configurations employed on the Sandia Z accelerator for (a) equation of state (EoS) experiments and (b) isentropic compression experiments (ICE).

The flyer plate section in figure 1.7(a) is actually just a thinner section of the top conductor; and it experiences the same force as the rest of the stripline. As it is thinner, it will deform and be accelerated towards the sample and will impart a shock
wave into the sample upon impact. In figure 1.7(b), the sample is directly connected to the stripline conductor and experiences a ramped compression pulse during the rise of the current pulse. In the above design each stripline is only suitable for a single shot and would need to be replaced after each shot; with careful design this can be optimised and wastage minimised.

### 1.4.1 Strip line Accelerator Overview

The Lorentz force either attracts or repels current carrying conductors as illustrated in figure 1.8, the force being dependent on the relative direction of the current flow in the conductors. The strip-line arrangement shown in figure 1.7 will be accelerated in the same manner, causing the conductors to push apart.

![Figure 1.8](image)

*Figure 1.8, (a) Parallel conductors (no current flowing), (b) Current flowing in the same direction (conductors attract), (c) Current flowing in opposite direction (conductors repel)*

Any pair of parallel conductors carrying currents in opposite directions will experience this force, as it results from the interaction of the current in one conductor with the magnetic field generated by the other.

For the arrangement shown in figure 1.7, the stripline is held firmly in place using appropriate fixings to ensure that only the desired section of the top conductor is free to move. This can also be achieved by making the flyer section out of thinner material.

### 1.4.2 Applicability to Foil-slap

The strip-line technique is the most promising of those reviewed so far as it can easily be scaled up to larger sized flyers without any significant alteration to the
underlying infrastructure. In addition, thinner foils can be used as the current levels necessary for acceleration are not necessarily high and are not applied for as long as in some of the other techniques.

Due to the established historical success of this technology and to its ease of implementation, it was seen as the most suitable option to develop for the purposes of this project and, and it is therefore looked at in more detail in chapters 2 - 5. The technique was previously used in the 1980s [2], when a very large foil-slap was used to perform the cold x-ray effects simulation. The series of experiments performed at AWE and described in the thesis utilise a much more comprehensive array of diagnostics and also concentrate on smaller samples (9 cm x 9 cm) to develop a better understanding of the technique.

1.5 Exploding Foil Accelerators

Sometimes referred to as electrically exploding foil accelerators (EEFAs), these utilise pulsed power to vaporise a foil. The resulting expanding vapour (or plasma) is used to accelerate a thin flyer usually made from Kapton or some other insulating material, to collide with a target.

1.5.1 Exploding Foil Accelerator Overview

Using this technique, ‘flyers’ have been accelerated to velocities in excess of 10km/s. The technology is currently widely used in the form of slapper detonators/initiators as a means of initiating high explosives. To achieve detonation, it is necessary to generate a very sharp shockwave [22]. Figure 1.9a shows a typical EEFA arrangement.

![Exploding Foil Accelerator Diagram](image)

*Figure 1.9a, A typical EEFA set up with no additional enhancements added.*
The above arrangement can be adjusted to make it more efficient by adding a barrel to contain the expanding vapour and so direct the liner (see figure 1.9b). Such modified systems are also referred to as electric guns [23], and as the barrel can comprise the rails and dielectric barriers it can act to further accelerate the plasma generated via the rail gun process.

Modifications often made to the above arrangement are indicated in figure 1.9b. Giving an indication of how these changes could be implemented but is only provided for illustrative purposes.

![Figure 1.9b EEFA set up with the barrel connected.](image)

When a capacitor bank is discharged through the metallic/exploding foil (smaller cross hatched section in figure 1.9a), the foil rapidly vaporises and can release up to 30 kJ/g of kinetic energy. When compared to the 6 kJ/g from a typical high explosive; the EEFA can yield up to 5 times the energy of a conventional explosive [24] on a gram for gram basis.

If electrically coupled to the transmission line, the barrel can further accelerate the plasma formed by the vaporisation of the foil and so enhances the kinetic energy of the flyer. The transfer of the exploded foil energy to the kinetic energy of the liner can be computed from an electrical analogy of the Gurney equations used to characterise the energy released from chemical explosives [25].

### 1.5.2 Applicability to Foil-slap

At present this technique is restricted to exploding very small foils and would need to be scaled up substantially to become useful for the size required in the present project. The main issue is that by increasing the size of the EEFA there is a much
larger risk from the explosion, causing problems with the structural integrity of the experiment.

As already mentioned, the explosive energy of the foil is much greater than that of conventional explosives. Using the EEF on a large sample will quickly reach an upper safe operating limit due to the size of the foil which will need to be vaporised.

This technique is not likely to be applicable to the present application as the explosion of a foil does not occur uniformly over a large surface area due to the generation of hot spots. Therefore the explosion is unlikely to cause uniform acceleration over a large surface area foil.

1.6. Comparison of proposed technologies for use in this project

Summary of techniques reviewed.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Rail Gun.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pros</strong></td>
<td>Well developed technology. Has been proven to be capable of accelerating both light and heavy projectiles effectively.</td>
</tr>
<tr>
<td><strong>Cons</strong></td>
<td>Not suitable for accelerating very thin armatures due to the high current and long conduction times needed to reach the necessary speeds, which will severely soften or melt them.</td>
</tr>
<tr>
<td><strong>Conclusion</strong></td>
<td>Technology is unsuitable for use in foil-slap experiments due to the higher currents and longer conduction times necessary.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Technique</th>
<th>Coil Gun (Reluctance and induction).</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pros</strong></td>
<td>Larger projectiles can be used than with the rail gun system. It is a non-contact accelerator and wear issues are greatly reduced.</td>
</tr>
<tr>
<td><strong>Cons</strong></td>
<td>The general assembly is designed to accelerate much larger projectiles than are necessary for this project. Also the foil-slap simulation requires large flat sheets to be accelerated and this form of induction launcher is not ideally suited for this purpose. Also complex timing systems would be needed if a multi-stage</td>
</tr>
</tbody>
</table>
system was required.

**Conclusion** The coil gun system is not an ideal choice to accelerate thin projectiles/armatures.

**Technique** Induction plate accelerator

**Pros** Effective for accelerating large flyers. May be easier for use with complex geometry flyers compared to other options due to possibility of using different coils at different sections.

**Cons** Controlling the uniformity of the induced current will be much more difficult, and will require much more preliminary work to understand this. Also the initial work will be on small flat flyers and so the added complexity of multiple coils is something which would ideally be avoided at this stage.

**Conclusion** At this stage this technique is left open as a potential technique when looking at a larger scale application. For the present small scale system it will not be utilised for the reasons explained above.

**Technique** Electrically Exploding Foil Accelerator.

**Pros** Very effective at accelerating thin flyers.

**Cons** Only useful for very small flyers, larger flyers would require larger foils and damage could be caused to other equipment by the foil explosion. Foil explosions are non-uniform due to hot spots.

**Conclusion** Currently used for flyers a few mm$^2$ in size. If much larger foils are exploded the mechanical force generated could lead to structural failure of the infrastructure. As the accelerating force cannot easily be controlled, the delivery of a uniform simultaneous impulse will prove very difficult.
<table>
<thead>
<tr>
<th>Technique</th>
<th>Stripline</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pros</strong></td>
<td>The technology has been used for similar experiments in the past. It can be relatively easily scaled up or down to suit the experimental needs. The flyer plate can be easily shaped to impact onto different geometry targets.</td>
</tr>
<tr>
<td><strong>Cons</strong></td>
<td>Ensuring planarity of the flyer is a real concern. A thin flyer is liable to deform during the acceleration phase if the current distribution is non-uniform across the flyer.</td>
</tr>
<tr>
<td><strong>Conclusion</strong></td>
<td>Identified as the most suitable of the techniques reviewed here. This technique will be used to carry out impulse tests on the initial small flat targets.</td>
</tr>
</tbody>
</table>

*Table 1.1, Summary of various technologies reviewed.*

1.7. Proposed way ahead

From the various techniques assessed, the stripline accelerator was chosen as the most appropriate option for the long term solution due to its relatively easy scaling and the potential to vary the target/flyer geometry with minimal change to the underlying infrastructure.

A stripline accelerator facility was designed and built at AWE to provide the capability to carry out controlled foil-slap material testing experiments. The facility named AMPERE was designed to be a versatile high current pulsed power generator. It enables experiments to be conducted on flat flyers as well as on more complex geometries, should this be required.

As explained in the abstract the aim of the experiments is to impart a **uniform, simultaneous impulse** into the target material, which will simulate the mechanical effects of cold x-ray exposure. Cold x-rays ablate a thin layer of material simultaneously and so the shockwave must be representative of this uniform vaporisation of material.

The impact tests will be conducted by accelerating thick aluminium foils (a few hundred microns thick) to several hundred of m/s before impacting the target. Laser
interferometry diagnostics will enable the rear surface of the target or the motion of the flyer to be monitored prior to impact.

The experimental arrangement consists of twelve General Atomics capacitors having a combined stored energy of 120kJ. Discharge of the capacitor bank was configured to produce a theoretical maximum current of 600kA. The facility is detailed in chapter 2.

A separate requirement of the research was to improve the driving current pulse shape and uniformity, as this affects the overall flyer performance. Together with the design of the experimental arrangement, another aspect which affects the planarity of the flyer plate is the uniformity of the current flowing through the conductors. In order to obtain uniform acceleration across the width of the flyer, a uniform current is necessary across the width. This is investigated in more detail in chapters 7 and 8 of the thesis, together with the development of a bespoke sensor to measure the current variation across the width of the transmission line.

The diagnostics used to measure the motion of the flyer and also the rear surface of the targets for the initial experiments include a laser interferometry based technique, developed by a separate group within AWE. However additional diagnostics (e.g. current and voltage probes) have been utilised by the author and are explained in chapter 6.
CHAPTER 2

Development of two independent electromagnetic stripline accelerator facilities

This chapter details the development of the two facilities which were developed as part of this work under the close supervision and under the technical lead of the author. The technical details of each facility as well as the commissioning of each are also detailed in this chapter.

As part of this project two separate facilities were developed at independent locations, the main reason being to utilise the technical expertise available at each location to help develop the various aspects of the technology. The two capacitor banks that were developed are based on the same physical principles and work in the same way but operate at different energy regimes. This enables any potential scaling issues to be identified; which will be necessary to allow an informed decision to be made on the potential development of a larger facility.

The principal stripline accelerator facility based at AWE enables controlled foil slap material testing experiments to be undertaken. The facility known as AMPERE is a high current pulsed power generator. At the same time a programme to refurbish the QUATTRO bank at Loughborough University was undertaken and was carried out under the supervision of the author. This enabled various arrangements and sensor technologies to be developed at Loughborough, prior to moving to AWE for use on AMPERE. Having the two sites available enabled different areas to be investigated in parallel. QUATTRO was a more experimental facility whilst AMPERE was a more established and permanent facility. Sections 2.1 and 2.2 describe each of the facilities in more detail.
2.1. Development of the AMPERE facility

The AMPERE facility was developed as a generic high-current source for use as a general-purpose research facility. Due to this it was unnecessary to keep the inductance as low as possible, which also allowed various safety features to be installed on the system making it very robust and safe. The author was responsible for the delivery of the facility and as the project manager was required to ensure it was delivered on time and on budget. The author was also responsible for the development of the novel current pulse shaping approach utilised (see chapter 4) as well as determining the best approach for commissioning the facility.

2.1.1 AMPERE electrical circuit

The schematic circuit diagram in figure 2.1 outlines the electrical circuit of the AMPERE generator. All the major generator circuit components are shown; but the safety systems and other infrastructure are omitted. Some components such as the current pulse shaping fuse and the flyer have time varying values due either to the energy deposition into them or their movement; the effects of these variables is also considered and described in chapter 5.

The circuit was modelled to understand its performance prior to being used for actual experiments. The computer model and results provided by it are discussed in chapters 3-5. The model developed is used to determine the required charging voltage and the physical dimensions of the fuse necessary to achieve a specified current pulse. Using the model can also ensure that the voltage spike induced by the sudden vaporisation of the fuse does not lead to a high voltage breakdown across the stripline. This is achieved by modelling the voltage, and tailoring the fuse to ensure this voltage trace is kept as smooth as possible. Care is taken to ensure that the reverse voltage on the bank is maintained within the manufacturers’ specifications.
Figure 2.1, Overview of AMPERE experimental circuit. Stripline components are indicated by the dotted line, dashed lines indicate individual sections of the circuit.

2.1.2 AMPERE CAD drawing

Figure 2.2 is a CAD drawing of the AMPERE facility. The bank and a single closing switch are arranged to feed the current pulse into a copper stripline, which initially has a spacing of 20 mm between the top and bottom conductors. This is reduced to a few millimetres at the foil acceleration region (figure 2.3). As the force is inversely related to the separation, the flyer experiences the largest accelerating force in the stripline. It should be noted that the flyer in figure 2.3 is a 30cm long section of the upper conductor and is clamped at each end. Due to the 1 dimensional approximation and the speed of the acceleration the central section of the flyer is not affected by the two clamped ends.

The current shaping fuse (see section 2.1.7) is known as the exploding foil dynamic resistor (EFDR); it makes up part of the stripline and is housed in a reinforced box to contain the fuse explosion. The EFDR also has a solid ceramic resistor across it to dissipate any residual energy in the system after it becomes open circuit. The same resistor can also absorb the total bank energy should a fuse not be installed.
Figure 2.2, CAD drawing of AMPERE with major components identified. The stripline is comprised of all the components on the table.

Figure 2.3, Cross sectional view of the foil flyer assembly, showing the spacing between the stripline conductors (top and bottom) being reduced at the flyer region.

AMPERE had a number of design iterations before the final design was achieved. The main requirements were that the bank had to be compact and that the maximum charging voltage should be sufficiently low to avoid the need for oil insulation. Using oil would have introduced a number of additional hazards, making it much more difficult to construct and subsequently work on the facility. To this end it was decided
that the capacitor voltage would be no higher than 40 kV and that the capacitors would be arranged in a ring to keep the system compact and to ensure that it would be easy to access all the main components (as shown in figure 2.2).

Figure 2.4 shows the initial positioning of the capacitors, including the aluminium framework designed to prevent them from falling over during use. This set the footprint of the facility, allowing the rest of the infrastructure to be installed around the capacitors.

![Figure 2.4, Capacitor assembly framework including central ground electrode connection.](image)

### 2.1.3 AMPERE capacitor safety

One major difference of this bank compared to previous designs used for similar purposes was the addition of safety fuses connected in series with each capacitor; which provide a major safety improvement over previous designs for flyer plate accelerators [26]. The purpose of these fuses was to keep the bank safe in the event of any internal capacitor failure. Should such a failure occur without the fuse in place the entire bank energy would be dumped into the short circuit inside the faulty capacitor, leading to an explosion, usually referred to as a catastrophic failure of the capacitor (as shown in figure 2.5) and is a major factor to be considered when designing high voltage capacitor banks.
The safety fuses used to protect each capacitor individually were specifically designed and provided by General Atomics and are well described in the literature [27]. AMPERE is designed to operate with a single switch. All twelve capacitors are connected in parallel to a common top plate (figure 2.6) which is where the switch is located.

2.1.4 AMPERE switching

Some facilities using multiple capacitors have individually switched capacitors [28]. Inherently this approach has a number of timing and jitter related issues and it is necessary to ensure that all the switches trigger sufficiently close together for these
issues not to affect the performance of the bank. If however, the current pulse needs to be shaped, every switch must be reliably fired in a very precise and controlled sequence. This adds further complications to timing and reproducibility of the discharges.

To overcome any timing issues on AMPERE, a single switch was used to couple all the capacitors to the load (Figure 2.7). An L3-pulsed Science rail gap switch was used. A previous iteration of this switch was used on the Atlas pulsed power facility at LANL [29].

![Fig 2.7, L3 rail gap switch installed in the centre of AMPERE capacitor bank.](image)

The low inductance and resistance of the switch is achieved by careful design of the rails and trigger electrode and the switching gas (the species, mix and pressure), which encourages multiple breakdown channels to be created before merging to form a single wide sheet of plasma across the width of the switch. The switch is quoted by the manufacturer as having an inductance of 20 nH, and a charge transfer capability of 10 C at a peak current of 1.2 MA, whereas an earlier design (the 40200, used on Atlas) was only rated at 750 kA. The switch is triggered using a bespoke 100 kV fast-rise trigger generator. The rise time is of the order of 100 ns, which is necessary to ensure the generation of the multiple streamers required to establish the low resistance/low inductance current path shown in figure 2.8.
Figure 2.8, Multiple trigger streamers which combine to produce the large plasma sheet that allows the full current to flow.

The switch was originally designed to be operated in sulphur hexa-fluoride (SF₆), but since this is now classed as a major greenhouse gas, it is no longer acceptable for use without employing costly and complicated gas recovery systems. The switch was therefore re-calibrated at the manufacturer for use with a mixture of oxygen/argon (10% oxygen: 90% argon), which is safe to use and can be directly vented to the atmosphere. The calibration curve for operating this switch is shown in figure 2.9, it was extrapolated from the data in the instruction manual and it has worked exceptionally well to date. The only problems occur when the gas mixture runs low and the relative ratio of the gases is no longer correct. This leads to misfires or self breakdown during charging.

Figure 2.9, Operational curve for L3 switch extrapolated and extended to fit the voltage range required.
2.1.5 AMPERE safety systems

The AMPERE facility was designed with numerous safety systems in place to minimise the risk of operator injury. The electrical safety and various dump systems incorporated into AMPERE are described in appendix A:

2.1.6 AMPERE SALUS System

The operation of the SALUS consists of a prescribed routine which forces the operator to walk around the exclusion zone whilst pressing buttons in a specific sequence to indicate that the area is clear. At the same time, a second person waits at the entrance of the exclusion zone to ensure that no one else enters.

Once the checks are complete the trigger generator and the HV power supply are powered up and armed, and the HV enclosure is locked. Once the HV cage is locked the gravity dumps are raised. The process of locking the cage releases a Castell key which is then used to power the control unit in the control room. The fire exit and door to the exclusion zone are linked to the SALUS and form part of the interlock system, therefore, should any of them be left open, the SALUS will not register as complete and no power will be sent to the control unit. If the SALUS is already complete, opening either of the doors will reset the system and put it into the safe mode. Whilst operators are in the control room, the HV enclosure and exclusion zone are constantly monitored through CCTV cameras.

Figure 2.10 shows a schematic layout of the AMPERE area, it highlights the route taken by the operator during the SALUS procedure and indicates the location of the SALUS buttons. The three interlocked doors are also identified, which if opened will reset the system once the SALUS is completed.
AMPERE SALUS layout

Figure 2.10, Schematic layout of AMPERE facility layout.

2.1.7 AMPERE electrical performance and current pulse damping

AMPERE is based on a series RLC circuit which has both a time varying resistance and inductance due to an exploding metallic fuse and the motion of a flyer plate respectively. A shot consists of charging all the capacitors in parallel, with the circuit open, followed by discharging them in parallel using a single triggered closing switch.
To protect the capacitors from an excessive number of voltage reversals it was necessary to introduce a component to quickly damp the current pulse. Otherwise the reversals would stress the dielectric, leading to a shorter capacitor life as seen in figure 2.11.

![Image](image-url)

**Figure 2.11, Effect of charging voltage (left) and voltage reversal (right) on capacitor life.**

One method of limiting the number and magnitude of reversals is to set the bank to a critically damped configuration. This would give just a single current peak which would decay away to zero. The major drawback of this option is apparent in figure 2.12 which shows that the peak current achieved for any given initial charging voltage is substantially lower for a critically damped discharge than for an underdamped case.
Damping can be achieved most simply by the addition of a series resistance, but other methods for obtaining a damped discharge while allowing the peak current performance to be maintained are available. These include crow-barring and dynamic resistance damping. The latter requires the resistance of the system to be drastically varied during the shot to give the desired performance. This is the method employed on AMPERE via the use of an exploding foil dynamic resistor (EFDR). A crowbar switch could be used but this has the added complication of having to rebuild the entire assembly for each shot. Using the EFDR requires only the fuse material to be replaced between shots with some cleaning of the contacts when necessary. Figure 2.13 shows the comparative current pulse shapes with and without the EFDR incorporated.

*Figure 2.12, AMPERE underdamped and critically damped performance.*

*Figure 2.13 – A typical current discharge profile for an under-damped LCR circuit with the EFDR augmented trace overlaid.*
The capacitors used on AMPERE are designed to withstand 60% voltage reversal and this is monitored to ensure that it is not exceeded. The EFDR is characterized by a very low initial resistance, which increases during the discharge until the deposited energy causes the foil to explode violently and become open circuit. There is also a fixed resistor in parallel with the fuse (see figures 2.1 and 2.2) which provides a parallel path for any remaining energy in the capacitors to be safely dissipated. It also limits undesired voltage spikes from being generated by limiting the rapid change in the current when the fuse opens. The EFDR initially allows a large current to flow through the circuit, thereby allowing maximum force to be exerted on the flyer. The eventual explosion of the foil leads to a current profile which is severely damped after the first current zero as indicated in figure 2.13.

There is presently no established theory to predict the performance of such a fuse and a series of empirical studies were carried out to provide a reliable understanding of this phenomenon in the particular physical environment of the AMPERE apparatus. Views of the fuse before and after its explosion are shown in figure 2.14.

![Image of fuse before and after explosion](image)

*Figure 2.14, EFDR before (left) and after (right) the fuse operation.*

The EFDR is required to become open circuit between the first current maximum and the first current zero, with the ideal moment being at the first current zero when only a small induced voltage is generated in the system. More realistically, a range during which the fuse operates is represented by the shaded area in figure 2.15.
Figure 2.15, Shaded area indicates the time during which the EFDR should operate to achieve a suitable current pulse.

Correct operation of the fuse will produce an output current pulse similar to the dotted waveform in figure 2.15 rather than the solid line. Modelling of the fuse is explained in chapter 4.

2.1.8 Commissioning the AMPERE facility

Before the facility could be used it had to be commissioned following an agreed set of procedures, although there were no specific criteria it could be benchmarked against. It was decided to commission the bank against the voltage hold off and its ability to effectively dump various levels of stored energy.

It was initially decided to commission ten of the twelve capacitors to 40 kV, and not the full bank of 12, as 10 capacitors were adequate for the initially planned trials. The procedure adopted required the capacitors to be charged and held at the charged voltage for much longer than in any normal operational mode. This tested the integrity of the HV insulation installed on the system. Subsequently the bank was charged and fired into the 1.6 Ω bypass resistor which has been designed to dissipate the total bank energy.

Details of commissioning the AMPERE facility are covered in Appendix B
2.2 QUATTRO bank overview

The capacitor bank at Loughborough University has been used for a number of experiments from imploding liners to various EM flyer plate and ring launchers. The bank is made of four BICC ES 189 capacitors which once formed part of the original flyer plate facility, GRIMM at AWE (GRIMM used 80 of these capacitors). The GRIMM bank had a total stored energy of 2 MJ when charged to 30 kV. After the bank was decommissioned, the capacitors were either disposed of or distributed to universities and used in smaller projects. Loughborough University acquired a number of them which have since been used in a variety of projects as part of the low inductance, high current driver named QUATTRO.

The QUATTRO bank comprises four capacitors connected in two parallel pairs. Each pair has its own switch (the same L3 switch used on AMPERE) but both are triggered by a common trigger generator to remove any timing issues. The QUATTRO bank has a total stored energy of 100 kJ when charged to 30 kV.

Figure 2.16, Schematic of QUATTRO bank, major components shown here including overall dimensions.
Figure 2.16 is an outline of the bank and the stripline feed to the load/flyer. Initially the bank was configured for liner implosion experiments and had to be reconfigured for flyer plate experiments. During this modification the opportunity was taken to fully refurbish the bank; it was taken apart and the insulation and any damaged conductors were removed and replaced. As with AMPERE the bank can be represented as a RLC circuit, with the equivalent circuit shown in figure 2.17.

![Figure 2.17, QUATTRO circuit diagram.](image)

### 2.2.1 QUATTRO Refurbishment

Figure 2.18 shows QUATTRO in one of its early arrangements. The load in this configuration was an imploding liner and no attempt was made to control the current pulse and it was left to oscillate. During the refurbishment a section was added the stripline to introduce current shaping. This could have taken the form of an array of exploding wires or a reusable stainless-steel section, which was investigated as a more permanent, non-destructive damping solution.
QUATTRO was initially designed to be of minimal inductance and resistance, which is why the conductors are kept as close together as possible. Due to this, the bank does not have the same safety features as AMPERE, although all the necessary safety features are included. QUATTRO was constructed to achieve its maximum output current with the shortest rise time and all the conductors are flat wide plates and the stripline has a very small separation between the top and bottom conductors. The drawback of this is that all the conductors experience a large force pushing them apart. To prevent any significant movement and subsequent damage to the stripline the majority of the stripline is loaded with heavy blocks to keep it in place during the discharge (figure 2.19). For safety reasons the bank was then covered with heavy duty netting to prevent any of the blocks from falling on the operator.
As mentioned above the stripline is loaded to prevent movement. The flyer section however, is free to move. A simple system to clamp the flyer had to be devised to allow it to be easily replaced without needing to dismantle the entire stripline, and to allow flyers of different widths to be used. The system relied on the applied pressure to maintain electrical contact, which allowed the flyer to be positioned and moved as needed (figure 2.20).

![Latest clamping method](image1)
![Original clamping method](image2)

*Figure 2.20, QUATTRO flyer section, two methods of connecting flyer shown*

There is a 2 mm separation between the flyer and the lower conductor, just as on AMPERE. Figure 2.20 highlights the two different methods of clamping the flyer down, both of which have a solid short at the end of the line. The original flyer was connected to the stripline by up to 9 screws (as seen on the right). The new method uses an aluminium bar and insulating material tied down at the 2 ends, with the applied pressure being sufficient to maintain the electrical contact.

The bank is operated remotely from an isolated control room via a fibre optic link. The fibre optics control the “picoscopes” (a USB/optical-fibre based oscilloscope which connects to a laptop to provide the interface), which are connected to a laptop to monitor the voltage on the bank during charging and discharging. The dump and isolating relays are activated using a fibre optic link as is the signal to the trigger generator. The fibre-optic system ensures that there is no electrical link between the HV lab and the control room; even the CCTV systems are connected using fibre optics. Figure 2.20 shows the feed through between the control room and the HV lab to indicate that no HV can find a path back the operator in the event of any failure.
Figure 2.21, HV and user areas only linked via optical cables to ensure operator safety.

QUATTRO does not have an automated SALUS but the laboratory does operate a two-man working procedure to ensure that no one can be locked inside the HV laboratory during operation of the facility. The door to the laboratory is also arranged as part of an interlocked system to ensure the lab is locked prior to the bank being energised.

2.2.2 QUATTRO current pulse damping

The underdamped, oscillatory discharge of QUATTRO is undesirable for the reasons explained in section 2.1.7, but due to the local environment and the nature of the bank, an EFDR cannot be implemented on QUATTRO. This therefore necessitated a separate assessment of non-destructive damping methods, which could be used to minimise the ringing. This was eventually achieved by using a stainless steel section designed using a model of the material resistivity from existing experimental data [30-33]. The model determines the change in resistivity of the stainless steel section during a current pulse due to energy deposition in the material leading to a temperature increase. Together with the computer model of the circuit (see chapter 3) this can be used to predict its overall performance. Figure 2.22 shows the stainless steel section installed as part of the stripline on QUATTRO, which inevitably heats up as the current flows. It may even reach temperatures where Mylar would melt, and a different insulating material, Kapton, was therefore used.
This is easily identified by its copper/brown colour in the figure below. Kapton is preferable to Mylar since, in addition to its higher temperature tolerance, it also has a greater dielectric breakdown strength.

Figure 2.22, Stainless steel section just before the flyer section, orange/brown insulation is Kapton.

The stainless steel used introduced a larger initial resistance into the circuit and so affects the current pulse from the beginning of the discharge. This causes an appreciable fall in the peak current. By accurately tailoring the steel section it is possible to reduce the ringing and also to keep the loss of peak current to a minimum. The ringing cannot be removed totally as is possible with the EFDR method, but it can be substantially reduced to be within the capacitor tolerances as shown in figure 2.23.

Figure 2.23, Modelled electrical discharge for the same initial conditions, with and without additional damping section.
The results shown in figure 2.23 are from the simple computer model described in chapter 3, which was used to design the most appropriate stainless-steel section. Once the initial resistance to be added and the properties of the stainless steel section were determined (i.e. the width, thickness and effective length) it was cut as shown below (figure 2.24) and a method to clamp it to the aluminium flyer plate was developed.

![Stainless steel section cut to this shape](image)

**Figure 2.24, This shows the original shape of the steel section and its connection to the aluminium flyer.**

Initial shots were conducted to test the effect of heating of the steel on the Kapton insulation to ensure that it would withstand the temperatures reached by the steel. The shots also confirmed that the system of clamping the flyer and the damping section was sufficiently strong.

Upon inspection of the arrangement one obvious feature noticed was that the 90° corners cut into the steel to reduce the width of the steel and connect it to the flyer, led to current concentrations and local vaporisation of the steel as is evident in figure 2.25.
Figure 2.25, Damaged stainless steel section, due to current hot-spots.

The final design was therefore altered to have a tapered section with an improved method of coupling the steel to the flyer via a copper contact strip, as shown in figures 2.26 and 2.27.

Figure 2.26, Modification made to the original steel section.

The damaged section was replaced with the tapered copper section to prevent localised hot spots from forming.
Figure 2.27, Final arrangement of steel and copper section.

The copper and steel were riveted together to provide a good contact.

2.2.3 QUATTRO Safety systems

QUATTRO has been developed with adequate safety systems in place. Appendix C describes the safety features incorporated into the QUATTRO bank as part of this work.

2.2.4 QUATTRO commissioning

As QUATTRO is a well-established facility, no specific commissioning procedures were essential to gain approval for its use. The refurbished facility was tested to a moderate charging voltage to ensure the insulation did not break down and a shot was fired to compare the current pulse obtained with the modelled value. This was also used as a basis to calibrate some of the specific electrical diagnostics developed as part of this bank. The diagnostics developed are explained in detail in chapter 6.

Figure 2.28 compares damped shots on both the facilities, AMPERE with the exploding fuse installed and QUATTRO with its new damping steel section, and shows that with appropriate damping both banks can produce a single current pulse which quickly damps to zero. It also shows that with the stainless steel section it is possible to get the desired performance using a non-destructive current shaping section.
It was considered that a different current pulse shape may be more appropriate to the foil slap experiments; however due to the pressure pulse shape being due to the deceleration of the flyer a simple sinusoidal discharge was used. Even though the two pulses in figure 2.46 have different rise times, the target arrangement can be altered to ensure they can both deliver the required impulse to the target. It should also be noted that the slower rise time was purposely built into the AMPERE system to encourage the current to be as uniform as possible across the width of the conductors at the time the flyer begins to accelerate.

*Figure 2.28, Modelled QUATTRO and AMPERE discharge currents (QUATTRO bank charged to 14 kV and AMPERE to 25 kV).*
CHAPTER 3

Accelerator system component characterisation

This chapter focusses on modelling the components of the AMPERE facility. Three equivalent approaches are shown for determining the component values and their benefits are discussed, it is identified in this chapter that the differential solver is the only method which will allow time varying components to be modelled for the later stages of the discharge. This chapter shows that the differential solver can accurately determine the circuit performance by comparing the modelled and measured current pulses as seen in section 3.4. In order to determine the various component values a method to extract the values was developed which used only directly measurable data (the current pulse).

Once the hardware was assembled as described in chapter 2, the electrical performance of each of the systems was investigated. This needed to be fully understood before the banks could be used to organise and conduct controlled experimental programmes.

To model the AMPERE facility or other similar facilities, the parameters of the individual components of the experimental arrangement need to be characterised. Total (or lumped) circuit values can be used to obtain the overall current pulse, but cannot be used to determine the voltage drop across various components of the stripline or to model any time varying parameters.

Initially a series of experiments were undertaken to determine the inductance and resistance of the individual components which formed the AMPERE facility, as described below.
3.1 AMPERE characterisation experiments

Experiments in which increasing sections of the experimental circuit could be added in stages were developed, allowing each component to be investigated in detail. The variation in the circuit response to a fixed input voltage between the shots enabled the change in the overall circuit parameters to be identified as described in section 3.2. This allowed the resistance and inductance of the additional sections to be obtained relatively easily.

A single aluminium block was used to short the stripline at different points as shown in figures 3.1.

![Aluminium block](image)

*Figure 3.1 Aluminium shorting block used to short the stripline at various positions.*

The block was securely clamped at various points across the stripline with the positions denoted by the labels shown in figure 3.2. When correctly implemented the aluminium block effectively changes the length of the stripline, making it possible over a series of shots to determine the effect of the additional sections on the electrical performance of the system.
Figure 3.2, Schematic showing the various points at which the stripline was shorted for characterisation.

Only the static values of the circuit parameters (resistance, inductance and capacitance) need to be considered for the preliminary tests, and no Ohmic heating or motion effects are investigated. To ensure this, the flyer and the EFDR were both replaced with stainless-steel plates, 2 mm thick (figure 3.3) which will maintain their shape and resistance during the relatively low level current pulse. The flyer section was 9 cm wide to keep the inductance the same as that for the actual experiments and the plate used for the EFDR was 15 cm wide, which was half the maximum width the system is designed to use.

Figure 3.3, Aluminium foil used for the Flyer plate (250 μm) is shown with the 2 mm thick steel section above it for comparison.
Experiments in which both the number of capacitors connected and the length of the stripline were varied were carried out. Electrical measurements taken during these experiments enabled values of the different circuit components to be determined as outlined below.

The aim was to establish a method of determining the circuit parameters from measurable data only (namely the current pulse). The methods used are described below.

### 3.1.1 Calculation from directly measurable parameters

Using standard circuit theory and a typical oscillatory current trace, the total circuit inductance and resistance for each particular arrangement were determined. The current trace is used to determine the decay constant \((\alpha)\) and the angular frequency \((\omega)\) of the discharge. As the circuit is altered by moving the shorting block along the transmission line (figure 3.2) the current pulse changes, thereby changing the values of \(\alpha\) and \(\omega\).

Standard expressions including \(\alpha\) and \(\omega\) for series RCL circuits are:

\[
\omega^2 + \alpha^2 = \frac{1}{LC} \tag{3.1}
\]

\[
\alpha^2 = \frac{R^2}{4L^2} \tag{3.2}
\]

The total inductance of the system can be expressed as having two components, one arising from the capacitor bank (denoted by the subscript “Bank”), which is a total value from the contribution of the individual capacitors and the other from the remaining stripline (denoted by the subscript “Line”). Equation 3.1 can then be expressed as:

\[
K_1 = \frac{1}{L_{\text{Bank}} + L_{\text{Line}}} = \left(\omega_1^2 + \alpha_1^2\right) \cdot C_{\text{Cap}}, \tag{3.3}
\]
For the general case when ‘n’ number of identical capacitor loops are used, the expression becomes;

\[ K_n = \frac{1}{L_{\text{bank}}/n + L_{\text{line}}} = \left(\omega_n^2 + \alpha_n^2\right)nC_{\text{cap}}, \text{ for } n \geq 1 \]  

(3.4)

where \( K_1 \) and \( K_n \) are the reciprocal total inductances for configurations using 1 and \( n \) capacitors respectively.

Expressions to determine the inductance and resistance of the circuit (with more than one capacitor loop connected) from the directly measured current pulse are shown below (equations 3.5 - 3.8). Initial tests used the “switch short” (SS) shots (see figure 3.1) where the aluminium block was clamped across the output from the switch creating the shortest possible circuit. These results represent the combination of the capacitor loops and the switch. It is clear that the switch and capacitor bank cannot be separated experimentally, but as shown below, analysis of the data allows the individual values to be obtained.

By determining the resistance and inductance of the of the switch short arrangement, it is then trivial to determine any additional inductance and/or resistance introduced into the system by analysing the change in circuit response.

The inductance and resistance terms shown below are for the inductance and resistance of the switch (subscript “Switch”) and the capacitor bank (subscript “Cap”).

\[ L_{\text{Switch}} = \frac{nK_1 - K_n}{(n-1)K_nK_1}, \text{ for } n \neq 1 \]  

(3.5)

\[ L_{\text{Cap}} = \frac{n(K_n - K_1)}{(n-1)K_nK_1}, \text{ for } n \neq 1 \]  

(3.6)
\[ R_{\text{Cap}} = \frac{2n(\alpha_n K_n - \alpha_1 K_1)}{(n-1)K_n K_1} \text{ for } n \neq 1 \] (3.7)

\[ R_{\text{Switch}} = \frac{2(\alpha_n n K_1 - \alpha_1 K_n)}{(n-1)K_n K_1} \text{ for } n \neq 1 \] (3.8)

The derivation of expressions 3.5-3.8 is given in Appendix D.

There are a number of methods to obtain the circuit parameters and these are discussed in Appendix E, the method which was ultimately used is described in this chapter.

### 3.2 Differential solver used to predict current trace

Instead of using a predetermined equation for the oscillatory discharge as shown in appendix E) the circuit response is modelled using a number of differential equations. This has a number of advantages including the possibility of adding further complex processes such as heating or motion as necessary.

The differential solver is set up for a lumped RLC circuit described by the following set of differential equations:

\[ \ddot{Q} = \frac{Q}{C} - \frac{IR}{L} \] (3.9)

\[ \dot{Q} = I \] (3.10)

In the above equations \( Q \) is the instantaneous charge stored in the capacitor (which is equal to \( C \) (capacitance) multiplied by \( V_0 \) (the charging voltage) and the other terms have their usual meanings (\( L \) is the inductance of the bank and \( R \) is the total resistance). In MathCAD the equations can only be solved if they are expressed as
a series of first-order differential equations. To aid this the following substitutions are made;

\[ y_0 \equiv Q, \]

\[ y_1 \equiv \frac{dQ}{dt} \equiv I, \]

and

\[ y_2 \equiv \frac{d^2Q}{dt^2} \equiv i, \]

these substitutions give rise to equations 3.11 and 3.12, which can be utilised by MathCAD:

\[ y_2 = \frac{d^2Q}{dt^2} = \frac{dy_1}{dt} = \frac{Q}{C} - \frac{IR}{L} \quad (3.11) \]

and

\[ \frac{dQ}{dt} = y_1 \quad (3.12) \]

For this application the Runge-Kutta adaptive solver is used to calculate the solutions. To check for accuracy a large number of points (i.e. a small time step) are initially used and the solution is then recalculated using significantly fewer points. If the two solutions are equal this gives confidence in the modelled results.

Details of the initial differential solve block used for the modelling of the bulk RLC circuit is shown in Appendix F.
3.2.1 MathCAD differential solver solutions

Equation 3.9 and 3.10 are entered into MathCAD as a pair of differential equations.

If we take the case where the initial charging voltage is 10 kV, and the capacitance is 13 $\mu$F. Using these values together with the necessary circuit parameters (fixed resistance and inductance) leads to the oscillatory discharge shown in figure 3.4:

![Figure 3.4, Predicted current trace for 10 kV, 13 $\mu$F arrangement.](image)

This discharge is predicted using the differential solver and looks sensible.

The solver and allow the affect of changing the variables to be easily determined, for instance if the resistance is increased a significantly damped discharge can be modelled as seen in figure 3.5:

![Figure 3.5, Predicted current trace with increased resistance to show damped performance.](image)
3.2.2 Parameter results from differential solver

Initial values of resistance and inductance were obtained using the fast capacitor discharge equations as in Appendix E. The differential solver method should yield the same result; however optimisation of the inductance and resistance was carried out again and slight discrepancies between the two methods were found.

![Image](image.png)

\textit{Figure 3.6, Experimental results (red) compared to MathCAD computer model (blue).}

As with the first method there is some slight deviation between the model and the experiment at the later stages. With the fixed resistance and inductance approach it is possible to get a good match over the first period. If needed, the differential solver can have a term added to it to account for the time varying features to make the model more representative of the experiment. This addition is explained in chapter 4, Using the differential solver (which still has fixed component values) produced the following results:
Table 3.1, Optimised resistance and inductance values of the sections of the stripline obtained using the differential solver in MathCAD.

3.2.3 Comparison of the two approaches

Table 3.2 shows the results using the two approaches on MathCAD, one being the differential solver and the other using the fast capacitor bank discharge approximations. The results from these two approaches should be the same but the differential solver allows for better comparison between the experimental and modelled results. The results are shown below:

<table>
<thead>
<tr>
<th>Component</th>
<th>MathCAD (Differential solver)</th>
<th>MathCAD (circuit approximations)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Component</td>
<td>Inductance (nH)</td>
</tr>
<tr>
<td>capacitor loop + switch</td>
<td>1385.0</td>
<td>52.52</td>
</tr>
<tr>
<td>capacitor loop</td>
<td>1216.0</td>
<td>51.29</td>
</tr>
<tr>
<td>switch</td>
<td>168.6</td>
<td>1.234</td>
</tr>
<tr>
<td>bridge</td>
<td>119.0</td>
<td>0.2048</td>
</tr>
<tr>
<td>dynamic resistor</td>
<td>170.5</td>
<td>2.269</td>
</tr>
<tr>
<td>remainder of stripline</td>
<td>62.48</td>
<td>1.732</td>
</tr>
<tr>
<td>transmission line</td>
<td>4705</td>
<td>15.68</td>
</tr>
</tbody>
</table>

Table 3.2, Comparison of results using the two MathCAD methods.
The results for the majority of the components are in close agreement as expected. The results obtained here are of course only valid when the component resistance and inductance do not change during the discharge.

When developing the model further to incorporate both heating and motion of the flyer, the results from table 3.1 will be used as the starting values in the initial model. The model is developed in stages, with the first addition being the inclusion of the time varying resistance which is dominated by the behaviour of the fuse. This is tackled in chapter 4 together with a detailed description of the static model which is used as the base from which the final model was created.

Chapter described the processes involved and the approaches considered for modelling the dynamic process required to achieve the desired current pulse damping. It explains the changes made to the computer mode and also takes into account the multiple current paths to ensure the correct current values are computed. The chapter also describes an alternative non-destructive component which has been used on the QUATTRO bank to achieve similar current pulse shaping as that on AMPERE.
CHAPTER 4

High current pulse shaping

This chapter describes the behaviour of very large exploding foils which have been used as current shaping fuses as part of this work. The modelling of such large foils for this purpose has not been documented elsewhere and is original work carried out by the author. The experiments needed to characterise the foil behaviour were designed and conducted by the author as was the development of the fuse holder and containment system to house the EFDR.

In section 4.1 The author describes the standard approach to modelling resistivity increase in metals and explains why this approach is not suitable for pulsed applications as well as giving a brief description of a non-destructive method of damping the current in these high current banks (section 4.4.1).

In chapter 3, a basic model was introduced which could be used to predict the electrical performance of a simple RLC circuit. It was tailored to model the performance of the AMPERE facility. As the model assumed no time varying components a perfect representation of the current pulse could not be generated. To improve the model, the next aspect that needs to be introduced is the time varying resistance of the system. To achieve this, a deeper understanding of the behaviour of the materials being used is required and this was obtained by carrying out a series of specific experiments designed and conducted by the author to provide the information necessary to enable the fuse section to be accurately modelled. These experiments are described in this chapter. Later on when the motion is to be included into the model, the time varying inductance will also need to be added, this is covered in chapter 5.

Damping the current pulse addresses the issues described in section 2.1.7., it also reduces the stress on the dielectric material within the capacitors, which is beneficial as excessive ringing can reduce the useful life of the capacitor bank [35].
A number of different current damping techniques can be used, of which two have been adopted. On AMPERE an EFDR (Exploding Foil Dynamic Resistor) is used as a current shaping component whereas on QUATTRO a non-destructive stainless steel section achieves a similar result. Both these approaches are described in this chapter. A robust understanding of the EFDR performance is necessary to produce a reliable, well controlled current pulse, and to avoid any issues arising due to inaccurate damper design. An inaccurate damper could lead to large voltage spikes, which can cause high voltage breakdown across the conductors, leading to damage to the facility.

As well as the benefits to the longevity of the facility, damping also helps with the analysis of the foil flyer experiments. Limiting the dynamics to a single EM acceleration event acting on the flyer, makes the analysis much simpler and allows the imparted shockwave to be determined more accurately.

A one dimensional (1D) model, building on what was described in chapter 3, is used to analyse both the electrical and mechanical performance of the experimental arrangement and has been named “ElectroMagnetic Strip Line Accelerator Program” (EMSLAP) Results from the model are also verified against an independent 2-D code [36]. The present 1D model assumes a uniform current distribution across the width of all components of the transmission line and so assumes a constant acceleration and uniform velocity across the flyer surface. The validity of this is discussed later in this chapter.

4.1 – Current shaping on AMPERE

An EFDR was implemented on AMPERE. Previous review of exploding foil research conducted [37], however in these cases the fuses are usually based on much thinner and smaller exploding wires or foils only a few mm$^3$ in volume. There is very little published literature on the performance of large area fuses, in some papers “very large” foils refer to exploding foils which are approximately 25 mm x 25 mm in size [38]. Since the EFDR is intended to be 30 cm long and can be up to 30 cm wide and is 50 µm thick, it is significantly larger than any of the exploding foils in the papers
referenced. Therefore a new approach to understand the fuse performance was necessary and this was developed by the author by analysing the empirical behaviour of the material in a high-current environment.

There are several theories which attempt to explain the fuse behaviour with the majority of these agreeing that any substance in contact with the fusible material can increase the potential conduction time of the foil before it becomes open circuit. This is attributed to the additional material restricting the expansion of the foil material and also absorbing the heat generated and so maintaining the conducting path for longer (termed “quenching”). There are also other theories which attempt to explain the time to burst using the action integral [39] (described briefly in this chapter).

4.1.1 EFDR quenching medium

The EFDR used on AMPERE is a very difficult component to fully understand; and its operation (as with all exploding foils) depends on its immediate surrounding environment, known as the quenching medium [40].

The conducting material is laminated to make it easier to handle (figure 4.1) and also to help contain the majority of the post-explosion vaporised foil material. This laminated section is housed in a box containing dry sand and covered by another layer of sand and a bolted down lid, totally encasing the fuse.

![Figure 4.1, EFDR fuse material encased in a 500 µm thick (2 x 250 µm sheets) laminating pouch.](image)
Use of a granular insulating medium around the fuse prevents a re-strike across the terminals by encouraging the metal vapour to condense onto the medium, and thus not provide an easy path for the current flow to re-establish. Figure 4.2 shows the EFDR housing box (the design of which was optimised by the author) with the fuse installed but without the second layer of sand above the fuse.

![Figure 4.2, Laminated EFDR held in position with sand between electrodes.](image)

### 4.1.2 Fuse action integral

The action integral is a way to understand the energy deposition into a material, it is more useful for slow energy deposition and is not ideal for pulsed discharges for the reasons described in this section.

When in use the foil does not simply slowly heat up, then melt and finally vaporise but rather goes through a much more violent process depending on a number of parameters. These include the conductor cross section, the length and width of the EFDR and the rate of energy deposition. The action integral is often used to define the performance of metallic fuses and other opening switches involving the sudden vaporisation of the conducting media [41].

The concept of the action integral provides some basic understanding of the fuse operation but is not sufficiently developed to be relied on for designing a fuse which has a surface area of the order of hundreds of cm$^2$. It is considered that every conducting material will vaporise once its critical action integral (“or action to burst”)
has been achieved; which has been demonstrated when working on fuses which are very thin or have a very small surface areas [42].

The action integral is simply the time integral of the square of the current during the discharge and is calculated from:

\[ A = \int I(t)^2 \, dt. \]  

(4.1)

In which \( I \) is the current flowing through the material. The 'specific' action is the value of the action per unit cross sectional area;

\[ \bar{A} = \int \frac{I(t)^2}{a^2} \, dt, \]  

where “a” is the cross sectional area of the fuse.  

(4.2)

The rate of energy deposition into the material also makes a significant contribution to the ‘time to burst’. This can be illustrated by considering the case when a given amount of energy is passed through a thin foil slowly; in which case the foil gradually heats up and possibly melts, alternatively, the same amount of energy is then rapidly deposited (quicker than the time required for the heat to be radiated or conducted away), in which case the fuse goes through a violent and explosive transition. This shows that it is not a sufficient criterion to merely reach a specific action integral but there is also a specific time period during which the critical action much be reached for the fuse to go open circuit. It is thus not valid to just quote critical action integral values for each material, as on their own they are meaningless.

Although there are numerous theories that predict the effects of pulsed high currents on wires and foils [39 - 42], each has a separate approach to tackling the problem. However all agree that the current density has a major role in determining the burst time. It is undeniable that the current density is directly linked to the resistivity of a material, thus more information needs to be obtained to understand the performance of the behaviour of large foils passing high pulsed currents.
Due to the lack of consistent data on the subject and the fact that the majority of existing work is based on exploding wires and not on wide foils, it was decided to use AMPERE to carry out a series of tests to determine the resistivity profile for the aluminium foil to be used for the EFDR. The empirical knowledge gained regarding exploding foils will be of great benefit to the field of high current pulsed power.

The empirical model which has been developed is capable of predicting the fuse performance to a high degree of accuracy for the wide range of fuse widths to be used in these experiments. It can therefore be used as a starting point to develop new models for similar materials.

4.1.3. Aluminium temperature – resistivity behaviour

Aluminium foils are widely used in both opening and closing switches and mass accelerators [43]. There are basic relationships (equation 4.3) for the temperature dependency of the resistivity of a given material, and by comparing this with experimentally measured values [44] an estimate can be obtained of the validity of the relationship.

\[ \rho = \rho_{20} \times (1 + \alpha(T - 20)) \],

(4.3)

where \( \alpha \) is the temperature co-efficient with units \( K^{-1} \) and \( \rho \) and \( \rho_{20} \) are the resistivities at temperature \( T(K) \) and at 20° C (293 K) respectively.

The alpha co-efficient describes the temperature dependent change of the conductivity for any given material. Usually the value is regarded as constant for a small temperature range but as can be seen in figure 4.4 this does not always correspond to experimental data over larger temperature ranges.

Using equation 4.3, the conductivity for aluminium was calculated, with \( \rho_{20} \) taken as \( 2.8 \times 10^{-8} \) Ωm and \( \alpha \) as \( 3.9 \times 10^{-3} \) \( K^{-1} \) [45]. Figure 4.3 shows the predicted conductivity variation as a function of temperature:
Figure 4.3, modelled Conductivity vs. temperature model for aluminium with constant alpha co-efficient.

The results from equation (4.3) are compared to measured data obtained from literature [44]; their comparison is shown in figure 4.4.

Figure 4.4, Theoretical Conductivity vs. temperature (equation 4.3) for aluminium with experimental points from literature [44] overlaid with the melting point indicated.

Figure 4.4 shows clearly that, although the experimental data matches the theory during the solid phase, there is a sudden deviation at the phase transition. A similar departure from the curve is also likely to appear at the boiling point, suggesting that
the alpha coefficient varies with either temperature or phase or both. This leads to
the requirement of conducting a series of controlled experiments to establish the
behaviour of the material as it passes through the phase changes; however this is
not in the realm of this research project.

Although the experimental data shown in figure 4.4 is for a controlled and relatively
slow process, the fact that there is a discontinuity, even in this case, indicates that a
faster pulsed discharge may exhibit even more complicated behaviour at the phase
transitions.

4.1.4 Fuse containment unit development

As mentioned in chapter 1, exploding foils release (gram for gram) up to 5 times
more explosive energy than high explosives. With this in mind the housing for the
EFDR must be designed to either withstand this explosive force or to have other
design features to enable it to survive the explosive event.

The preliminary design of the fuse containment unit is shown in figure 4.5:

![Figure 4.5, Initial design for the EFDR](image)

The final assembly shown in figure 4.6 was designed to be much stronger than that
of design of figure 4.5 to withstand a larger explosive event.
The EFDR box is made from 10G40 (usually called G10), a laminated glass fibre composite material commercially known as Tufnall [46] and is the insulator of choice for many pulsed power machines in the US. It also has very high mechanical strength and excellent HV insulating properties.

To help contain the explosion and to limit the strain on the G10 box, the author modified the initial design of the containment box to allow venting of the vapour pressure generated during the explosion.

The first measure implemented was to leave the corners inside the EFDR box empty (highlighted areas in figure 4.7) to allow the sand to move into them prior to pushing up on the lid.
For this method the lid was still fixed down with four M6 (6mm machine thread) bolts; in the belief that once the sand has expanded into the four corners the pressure would have fallen too low to put pressure on the lid.

The above solution worked well for a number of small foils; however the explosive force released from larger foils exerted excessive mechanical forces on the fasteners holding the lid down, leading to the mechanical damage to the fuse holder evident in figure 4.8. The force on the EFDR lid was sufficient to pull out the Helicoils used to fix the lid to the rest of the assembly; Helicoils are a standard method of introducing stronger threads into a normally weaker material.

![Helicoil pulled out through the G10 material.](image)

*Figure 4.8 Damaged Helicoil due to excessive upwards force on lid.*

In order to sufficiently reduce the strain on the equipment it was decided to change the system and to intentionally allow some movement of the lid. A modified lid was then held down using eight high strength springs (see figure 4.9) which allow it to move up and so vent the gas pressure. This method is not dissimilar to the way in which a pressure relief valve operates, which vents pressure once it has reached a critical level.
Once the pressure relief system was installed a method to capture any ejected material from the box was also needed, and this was achieved by mounting a thick sheet of Mylar or Polyethylene to the top of the springs and fixed to the optical table. This formed a shield to prevent sand and other debris from being ejected across the experimental area. The arrangement is shown in figure 4.10.

With these additions in place the EFDR can be operated without any major issues. Further additions included the use of heat resistant Kapton as the insulation material between the stripline conductors, to protect the insulation from any hot debris ejected from the EFDR box.
Figure 4.11 shows the final assembly with all the features labelled. The polycarbonate shields at each end of the EFDR box limit the hot material being ejected out the ends; however, should this occur, the Kapton will not melt and will maintain electrical insulation for subsequent shots.

4.2 EFDR empirical model development

Once the values of the fixed circuit components had been determined (chapter 3); a series of experiments were carried out to analyse the fuse performance and to develop an empirical model for use in the present experiments.

To work accurately, the varying resistance must take into account the energy being deposited into the fuse or flyer material and then determine the effect this has on the overall resistance. The change in resistance affects the rate at which energy is deposited (as Joule heating) and needs to be included as part of the differential solver.

An empirical model was developed by comparison between the computer model and experimental results with the initial resistivity profile used as the starting point; originally used for thin wires and provided by Professor Bucur Novac at
Loughborough University [47]. The profile was extensively modified until the modelled results matched the measured results from the initial EFDR shots.

The EFDR is used to tailor the current pulse and ideally totally damp the current at the first current zero (see figure 4.12).

![Figure 4.12](image)

*Figure 4.12, the dotted line (red) shows the ideal effect of using an EFDR compared to the standard oscillatory discharge (blue).*

Figure 4.12 shows an idealised current trace with no ringing of the current whatsoever, but in practice this is not possible and some current reversal is always observed as shown in figure 4.13.

![Figure 4.13](image)

*Figure 4.13, Typical result from EFDR damped discharge.*
Figure 4.13 shows that although the EFDR allows the complete first half period of the discharge to be only minimally damped, this is followed by severe damping of the current from the first current zero onwards.

4.2.1 – Changes to the MathCAD model

A number of changes were made to the MathCAD model developed in chapter 3. The first introduction was a section to characterise the physical dimensions of the fuse as well as to determine its initial resistance at room temperature.

The initial resistance of the fuse/EFDR \((R_0)\) can be calculated using the standard equation and the physical dimensions of the fuse as shown below:

\[
R = \frac{\rho \cdot l}{a}
\]  

Where \(R\) is the resistance, \(\rho\) is the resistivity of the material, \(l\) is the length and \(a\) is the cross sectional area.

At this stage the length and thickness of the fuse are fixed at 30 cm and 50 \(\mu\)m respectively and only the width will be varied.

To ensure that only the EFDR has a time varying resistance, the flyer section on the facility was replaced with a thicker stainless steel section (2 mm think) as shown in figure 4.14.

*Figure 4.14, Calibration shot with the thin flyer replaced by a thick steel plate.*
4.2.2 Exploding wire resistivity (Aluminium)

Initially some data points relating the dynamic resistance versus specific energy density (used to model exploding wires [47]) were used as a starting point for the model (figure 4.15). The multiplication factor is the resistance at the defined energy density divided by the resistance at room temperature ($R/R_0$).

![Graph of Specific energy density vs Multiplication factor](image)

*Figure 4.15, Initial resistance profile for an exploding Aluminium wire.*

The model shown in section 3.4 was modified to include a Joule heating term, this was used to determine the energy dissipated in the resistive section and then dividing this by the mass of the foil allows the specific energy density to be determined. The result is then used with the resistivity profile to determine the predicted resistance relative to the room temperature resistance (assuming no heat is radiated or conducted during the energy deposition).

The profile (figure 4.15) was adjusted until the predicted current pulse was in agreement with the measured current trace and the final resistivity profile was then also used to model the resistance of the flyer section as both were made from pure aluminium. The changes made to the model are covered in the following section.
4.2.3 Changes to the Differential Solver

In chapter 3 (section 3.4.1), the solver developed calculated the RLC discharge of a typical circuit with specific fixed circuit values. Figure 4.16 shows the modified solver. The changes introduced are the addition of two lines which determine the energy deposited into a metallic foil (both the flyer and EFDR sections are shown here) but the mass of the steel can be set very high to keep the resistance of that section constant during the discharge. The total resistance in the system is also modified to include the parallel bypass resistor (see equation 4.5).

The differential equations describing the circuit are given below including the expressions for determining the energy density of the thin metallic components (it is assumed the thicker components do not experience any significant heating).

\[
\ddot{Q} = -\frac{Q}{C} + \left(\frac{1}{R_{\text{EFDR}}(w_{\text{EFDR}})} + \frac{1}{R_{\text{parallel}}^{-1}}\right)I^2 + R_{\text{Flyer}}(w_{\text{Flyer}})I^2
\]  

(4.5)

Where \( w \) is the internal energy density of the fuse/flyer material and is calculated as shown in equations (4.7) and (4.8).

As earlier the current is described in terms of the first derivative of the charge:

\[
\dot{Q} = I
\]  

(4.6)

\[
w_{\text{EFDR}} = \frac{R_{\text{EFDR}}I^2}{m_{\text{EFDR}}}
\]  

(4.7)

\[
w_{\text{Flyer}} = \frac{R_{\text{Flyer}}I^2}{m_{\text{Flyer}}}
\]  

(4.8)
The initial conditions for the circuit are that the current and the deposited energy in both components is zero and that the capacitor is initially charged to \( v_0 \). This can be seen in figure 4.16:

\[
D(t, y) := \begin{bmatrix}
\frac{y}{\text{cap}} + \left[ RT(y_2) + n_{\text{fl}}(y_3) \right] y_0 \\
\text{ind} \left( y_2 - y_0 \right)^2 \\
\text{mf} \\
\text{mfy}
\end{bmatrix}
\]

\[ RT = \left( \frac{1}{R_{\text{EFDR}}} + \frac{1}{R_{\text{parallel}}} \right)^{-1} \]  

(4.9)

Figure 4.16. Differential solver constructed to calculate both the current and the energy deposited in the flyer and the fuse.

The initial values in array “\( y \)” are for the following parameters:

- \( y_0 \) – Current flowing in the circuit
- \( y_1 \) – Instantaneous charge in the capacitors
- \( y_2 \) – Energy density in fuse
- \( y_3 \) – Energy density in flyer

Equation (4.9) is the combined resistance of the EFDR and the parallel resistor connected as shown in figure 2.1 and positioned as shown in figure 2.2. The initial resistivity profile (figure 4.15) is introduced as a table within the MathCAD file itself. A number of versions of this resistivity profile were developed prior to reaching the final version shown in figure 4.17. It should be noted that the profile is dependent on
a number of factors and will be most accurate for fuses which are made from 50 \( \mu \text{m} \) thick aluminium foil (99.5\% purity), encased in a 500 \( \mu \text{m} \) laminate and covered by dry sand to quench the explosion of the fuse material.

Figure 4.17 shows the final optimised resistivity profile which was generated by looking at the region of interest from figure 4.15 and making incremental changes to it and comparing measured current pulse to modelled results and making the required changes to the resistivity profile until good agreement was obtained.

![Resistivity Profile](image)

*Figure 4.17, Final resistivity profile for the 50 \( \mu \text{m} \) thick Aluminium used for the fuse.*

Figure 4.17 shows the resistivity profile which describes the behaviour of the 50 \( \mu \text{m} \) foil used in these experiments.

### 4.2.4 Initial results from differential solver

The results obtained using the differential solver (figure 4.16); enable the resistivity profile (figure 4.16) to be adjusted until a good match with experimental data is obtained. Figure 4.18 shows the results using the original resistivity profile.
As can be seen the original resistivity model (shown in figure 4.15) fails to predict the operation of the EFDR accurately. This model was therefore optimised and incremental changes made to the profile to obtain a more representative model for the EFDR.

Figure 4.19 shows the results from the optimised resistivity model (as shown in figure 4.17) for the same discharge as shown in figure 4.18.
As can be seen in figure 4.19, modification of the resistivity profile leads to a more accurate representation of the electrical performance especially during the first half period.

The performance of the resistivity profile has been investigated for a range of fuse widths and charging voltages, figures 4.20 and 4.21 show its performance for a narrower and a wider EFDR width.

![Model vs Experiment Comparison]

*Figure 4.20, Modelled and experimental results compared for fuse width: 5 cm, charging voltage 13 kV.*

The model predicts the performance of the narrower EFDR more accurately even after the first half period.

Figure 4.21 shows the performance of a much wider EFDR and once again the performance of the model is very good, however there is some deviation prior to the first zero crossing.
Figure 4.21, Modelled and experimental results compared, fuse width set to 10.8 cm, charging voltage of 31 kV.

Figures 4.20 and 4.21 show good agreement between the modelled and measured data. This indicates that the resistivity profile together with the differential solver can be successfully applied to a wide range of initial conditions.

At this stage the computer model assumes that the current flowing through the EFDR and the flyer section is exactly the same. In reality this is not the case and is due to the parallel path across the resistor, which provides an alternative route for the current to flow. This causes a lower current to flow through the EFDR compared to the flyer during the discharge.

Section 4.3 attempts to improve the model shown in figure 4.16 by analysing the current flow in the two parallel paths. This enables an even more accurate prediction of the current through the fuse and a more reliable prediction of the fuse behaviour.

4.3 Current flow modelling

To determine the most accurate EFDR performance, the current flowing in both of the parallel paths needs to be considered. In addition, a set of equations for the voltage drop across the fuse and also one for the general voltage drop in the full
stripline (using the Kirchhoff loop rule) were established and solved to determine the required data.

4.3.1 – Model development

Figure 4.22 identifies the position on the stripline where the current is divided between the two paths, with some going to the parallel resistor. This resistor ensures that there is no sudden halt to the current flow, which otherwise would lead to large induced voltage spikes during the fuse explosion.

The distribution of current between the two paths (\(I_p\) and \(I_F\)) depends on the resistances and inductances of the two branches.

To express the voltage drop across the two points shown in figure 4.22, either the voltage drop across the EFDR (\(V_f\)) or that across the parallel resistor (\(V_p\)) can be considered which are of course identical. Thus:

\[
V_f = I_f \cdot R_f + \frac{dI_f}{dt}
\]  

(4.10)

\[
V_p = I_p \cdot R_p + L_{\text{trans}} \cdot \frac{dI_p}{dt}
\]  

(4.11)
where subscripts ‘p’ and ‘trans’ denote the parallel paths and subscript ‘f’ denotes
the EFDR path.

Finally, the voltage drop across the entire circuit, considering the parallel resistor
path is:

\[
\left( \frac{O}{C} \right) = -(\left( R_{\text{bank}} + R_{\text{fly}} \right) I_T) + \left( \left( L_{\text{bank}} + L_{\text{fly}} \right) \frac{dL_T}{dt} \right) + \left( R_p \cdot I_p + L_{\text{trans}} \cdot \frac{dI_p}{dt} \right) + \left( I_T \cdot \frac{dL_{\text{fly}}}{dt} \right) \quad (4.12)
\]

The voltage drop across the various components are calculated and equation (4.12)
includes terms for the resistance and inductance of the bank, the flyer, the parallel
resistor, the transmission line connecting the parallel resistor and also includes a
term for the effect of the changing inductance should the flyer move. The total
current, and also the rate of change of the total current and the rate of change of
current in parallel path is also required.

The above equations are put into a separate MathCAD solver and solutions for \( \frac{dI_p}{dt} \)
(rate of change of current in the parallel path) and \( \frac{dI_f}{dt} \) (rate of change of current in
the EFDR path) are obtained by solving equation (4.12) simultaneously with equation
(4.11) put equal to equation (4.10),

MathCAD can readily solve the simultaneous equations and produce expressions
which then allow the EFDR performance to be modelled more accurately.

Below is a section from MathCAD which uses equations (4.10) – (4.12) to determine
expressions to calculate the rate of change of current in the two paths via a symbolic
solver built into MathCAD.
Given

\[ \text{Voltage drop across Resistor} = \text{Voltage drop across EFDR} \]

\[ Y_1^\text{cap} = \left[ \frac{(t - R_f y_f) \cdot (p + L_f)}{x_F + (t - R_f y_f) \cdot (p + L_f)} \right] \]

Total circuit voltage drop

\[
\begin{align*}
\text{Expressions for determining the rate of change of current in the two paths} \\
\text{Given} \quad \frac{1}{\text{cap}} \frac{d}{dt} \left( \text{cap} \right) = \frac{1}{\text{cap}} \frac{d}{dt} \left( \text{cap} \right) \\
\end{align*}
\]

*MathCAD solutions for equation (4.12) putting (4.10) equal to (4.11).*

The terms used in the above results from MathCAD are defined below:

- **RP** – Resistance of parallel resistor
- **Lt** – Inductance of transmission line connecting the parallel resistor to the EFDR
- **Lf** – Inductance of EFDR section
- **xF** – Rate of change of current in the EFDR path
- **xP** – Rate of change of current in the parallel path
- **IP** – Current in parallel path
- **IF** – Current in the EFDR path
- **V0** – Charging voltage
- **Q** – Charge on capacitors
- **Cap** – Total capacitance
- **r** – Bank resistance
- **rfl** – Flyer resistance
- **ind** – Total inductance of bank
- **Lfly** – Inductance of flyer
- **xL** – Rate of change of inductance of flyer

To utilise the expressions above a new solver is created which uses them to determine the current in each path independently, whilst also taking into account the changing inductance and resistance. This method should provide a more accurate
model of the performance of the EFDR as the current in this component has been decoupled from the rest of the circuit.

The final term of equation (4.12) accounts for the change in inductance of the stripline due to the motion of the flyer (as the stripline separation increases). This is essential, as both inductance and resistance affect the current flowing through the various parts of the circuit.

The inductance approximation for a flat stripline conductor is used in this calculation and can be found in the literature [48].

4.3.2 – Modified solver to account for dual current paths

Using the expressions derived previously and adding the various dependencies for each term in the expression a new differential solver was created. The new updated solver is shown below, and includes all the time varying terms as well as modelling the current flowing through the 2 parallel paths.

![MathCAD solver showing both current paths and the energy deposited into the fuse and the flyer.](image)

The terms have been replaced with the appropriate array values (i.e. \(y_0, y_n\)). In this particular case they have the following definitions:

- \(y_0\) – Current in the EFDR path
- \(y_1\) – Total charge in the capacitors
- \(y_2\) – Energy density in the EFDR
\text{y}_3 - \text{Energy density in the Flyer}
\text{y}_4 - \text{Current in the parallel path}
\text{y}_5 - \text{Velocity of flyer}\text{*}
\text{y}_6 - \text{Displacement of flyer}\text{*}

*It should be noted that \text{y}_5 \text{ and } \text{y}_6 \text{ are not shown in the above solver but the terms which rely on them have been identified. Those additions to the solver are described in chapter 5.}

The results from the updated solver are shown in the next section.

4.3.3 Results from the modified solver

The electrical performance of the model when using the optimised resistivity profile (figure 4.17) is illustrated in figures 4.23 – 4.35

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{current_time_plot.png}
\caption{Capacitors charged to 22.5 kV, 8.5 cm fuse (peak current \sim 270 kA)}
\end{figure}

The results in figure 4.23 are for 10 capacitors charged to 22.5 kV with an 8.5 cm fuse (peak current \sim 270kA). The red (dashed) trace is the model and the black trace is the actual data. The results are for the same experimental arrangement as in figure 4.19; and show the improvement in the model due to considering an accurate current distribution.
The accuracy of the new model is checked by comparing the modelled and measured performance for various different experimental configurations.

Figure 4.24, Capacitors charged to 25 kV, 8.6 cm fuse (peak current ~300 kA),

The peak current is measured as 300 kA and the model predicts a peak of 296 kA.

Figure 4.25, Capacitors charged to 37 kV, 13.15 cm fuse (peak current ~453 kA)

The above results show that there is less than 2% difference between the peak modelled and measured current value. This level of accuracy was achieved for a range of different initial conditions.
The difference between the measured and modelled peak current value is 7 kA (less than 2% discrepancy).

These results show that the model developed for AMPERE is now very accurate for a range of initial parameters and it therefore can be used to plan shots within this range. They also show accurate scaling and should allow the results from future experiments to be predicted with sufficient accuracy.

It is also capable of determining the 1-D motion of the flyer as described in chapter 5. The model developed was also used (with slight modifications) to represent the QUATTRO bank. The modifications needed to model this bank are detailed in section 4.4.

4.3.4 Voltage across bridge

Another aspect of the system modelled was the voltage across the stripline at the bridge section (located immediately after the switch and before the fuse) as indicated in figure 4.27.
The voltage between any two points in the stripline can be readily modelled as all the individual sections of the stripline were previously characterised in chapter 3.

It is crucial to monitor the voltage across the stripline as this indicates when the EFDR becomes open circuit and can help tailor the performance of this crucial component. The voltage is also modelled to ensure that the voltage spike generated by the interruption of the current is kept below the breakdown voltage of the stripline.

The voltage across the stripline is modelled by taking into account the time dependant resistive and inductive contributions from the EFDR, the flyer and the return copper conductor of the stripline. The equation used in the model is shown below;

\[ V_{\text{bridge}} := \text{Fuse} R_j I_{\text{f}} + \left[ (L_{\text{dr}} + L_{\text{f}})(F_{\text{didt}}) \right] + \left[ (F_{\text{fly}} + R_{\text{dr}} + F_{\text{didt}} \cdot I_{T}) \right] + \text{indf}_{\text{fly}} \cdot \text{didt} \]

(Note the EFDR term is referred to as 'Fuse' in the above equation).  

\[ (4.13) \]

\( V_{\text{bridge}} \) is the voltage drop across the stripline just after the bridge (see figure 4.33).

\( \text{Fuse} R \) is the resistance of the EFDR.

\( L_{\text{f}} \) and \( L_{\text{dr}} \) are the inductance of the EFDR and the EFDR holder sections.

\( F_{\text{fly}} \) and \( R_{\text{dr}} \) are the resistance of the flyer and the EFDR holder section.

\( \text{indf}_{\text{fly}} \) is the inductance of the flyer.

\( I_{\text{f}} \) and \( F_{\text{didt}} \) are the current and rate of change of current in the EFDR path.

\( I_{T} \) and \( \text{didt} \) are the total current and rate of change of total current in the circuit.
The measured voltage and the result provided by equation (4.13) are compared in figure 4.28:

**Figure 4.28, Measured and modelled voltage across stripline for a 23.7 kV charge voltage using an 8.1 cm wide fuse.**

The optimised model provides very good agreement with the measured voltage across the stripline. The model can also be used to ensure that this voltage does not lead to a HV breakdown across it due to any large voltage spikes induced during the operation of the EFDR.

Should an EFDR be too narrow for the charging voltage used a result similar to that seen in figure 4.29 would be generate; as seen there is a significant spike in the voltage during the discharge, thus increasing the probability of an electrical breakdown across the stripline conductors. The model can therefore be used to avoid such events from occurring.

**Figure 4.29, Modelled voltage across stripline for 23.7 kV charging voltage but using a 7.1 cm fuse instead.**
The measured data in figure 4.29 allows a comparison to be made between the performance of a correctly sized fuse compared to one which is too narrow. In this case the EFDR becomes open circuit whilst there is still significant current flowing leading to the large voltage spike, which could lead to a breakdown across the stripline.

4.4 QUATTRO modelling

As outlined in chapter 2, the QUATTRO bank has a lower total energy than AMPERE; it also has a much lower resistance and inductance, with roughly 3 mΩ of resistance and 30 nH inductance. As such it can produce much higher currents with a much shorter rise time than can be obtained from AMPERE.

Considering the principle of the action integral implies that the critical action integral would be achieved much faster on QUATTRO than on AMPERE. Also due to the higher currents the foil explosion is more energetic and so is much more difficult to contain.

For completeness the modelled performance of various fuse widths on the QUATTRO bank are shown in figure 4.30. The fuses modelled are 100 µm thick aluminium foil and the various simulated current traces are all for the same initial charging voltage of 25kV.

![Figure 4.30, Modelled performance of QUATTRO bank with various EFDR widths.](image-url)
Figure 4.36 shows that it is possible to determine a suitably sized EFDR for the QUATTRO bank by using the model developed for AMPERE. However due to the facility requirements and various safety considerations it was decided that a non-destructive system of damping the bank should be developed.

4.4.1 – Non-Destructive damping

To obtain a less ‘dynamic’ method of damping, it was initially suggested that a resistive section should be added to the bank to reduce the oscillatory discharge. Using basic RLC circuit theory, an appropriate constant resistance can be added to the bank to obtain the damping. It is possible to obtain under-damped, over-damped or critically-damped response as indicated in figure 4.31.

Adding a known resistance to the computer model is trivial. It is also a simple task to add the necessary resistance to the experimental arrangement to achieve the desired discharge.

Using this approach, a suitably sized resistive section (‘damper’) was designed and modelled, leading to a more tailored performance of the QUATTRO bank as shown
in figure 4.32. This section can be made from any suitable conductive material which has a sufficiently high resistivity, such as stainless steel or nichrome.

An initial 6-8 mΩ of additional resistance (at room temperature) is added to the system. This ensures an acceptable level of damping (as shown in figure 4.32), whilst minimising the loss in peak current.

![Graph showing current vs. time with and without added circuit resistance]

*Figure 4.32, Modelled optimised damping using fixed value damper on QUATTRO.*

At this stage it was decided to investigate stainless steel as the material to create the damping section. This was because it is more readily available in the required form (a thin, wide foil).

### 4.4.2 – Damping using stainless steel

The main difference between the EFDR and the non-destructive damper is that the latter is reusable, making for repeatable and controlled experiments. Developing a successful damper requires an understanding of the material response to the high current pulse. By using the room temperature resistivity of the stainless steel, the starting resistance can be determined, however the final resistance it will reach is not known. Initially it was assumed that the section would remain at a constant resistance during the discharge. This allowed the damping section to be estimated to produce the desired level of damping, similar to the idea case shown in figure 4.31. Obviously the assumption of a constant resistance is not accurate; as was
explained in section 4.2 for the EFDR. To determine the most accurate performance of this material a range of experimental data was obtained [20-33].

Another material which could be used is nichrome, which has a similar melting temperature and specific heat capacity and density to stainless steel but a higher room temperature resistivity. One of the main drawbacks of nichrome is that it is usually supplied in wire form and wide foils are not easy to source. For comparison the relative resistivity increase of nichrome [49] is compared to stainless steel in figure 4.33.

![Figure 4.33, Resistivity – temperature relation for stainless steel and nichrome, figure showing experimental data.](image)

Using the resistivity values as well as the specific heat capacity of each of the materials the relative resistivity increase with temperature can be calculated, this is shown in figure 4.34. As seen even though nichrome has a higher resistivity the relative increase in resistance for a given temperature increase is higher for stainless steel making it the most suitable material to use.
Figure 4.34 shows the relative increase in the electrical resistivity of stainless steel and nichrome with increasing temperature. Even though nichrome has a larger value for its electrical resistivity at any given temperature, the rate at which the resistance changes allows steel to deliver a larger dynamic range when heated. For this reason and due to the availability of stainless steel, it was used for all further work.

4.4.3 – Installation of damper on QUATTRO bank

The initial attempt to damp the discharge used 6 mΩ of additional resistance added to the circuit; this was in the form of a stainless steel section cut to a specific size and installed in line with the upper stripline conductor as shown in figure 4.35.
Figure 4.35, *Original steel section installed on the QUATTRO bank.*

Due to the shape of the stainless steel section, hot spots were generated leading to the damage shown in figure 4.36.

![Vaporised Steel in corners due to current concentration](image)

Vaporised Steel in corners due to current concentration

*Figure 4.36, Localised damage caused by localised hot spots.*

The steel section was modified and installed on the QUATTRO facility. The protect the electrical insulation between the upper and lower stripline conductors, Kapton was used instead of Mylar (figure 4.37). Kapton was not used solely for its high voltage breakdown characteristics, but also for its ability to withstand high temperatures.
After this modification a number of shots were performed and the new section was assessed for damage. It was found that this design had no localised hot spots, and the Kapton had not deteriorated due to the high temperatures reached by the steel.

### 4.4.4 – Stainless steel resistivity model

Experimental data for the variation of stainless steel resistivity was obtained over a large temperature range; and used to model the performance of the damping section. Figure 4.38 shows how the resistivity of the stainless steel varies with temperature as given in a number of different sources [30-33].

The temperature of the steel can be easily related to the specific energy density of the material using its specific heat capacity, thus allowing it to be used in the model already created.
The specific heat of stainless steel is also a function of temperature and is shown below [50]:

*Figure 4.39, Specific heat capacity of stainless steel for the temperature range 298 K to 1700 K.*

Using the specific heat values shown in Figure 4.39 it is possible to determine a continuous variation of the specific heat with respect to the internal energy density of the steel (figure 4.40).

*Figure 4.40, Specific heat of stainless steel with varying specific energy density, between 0 K and 2000 K*
Considering the experimental data for the resistivity and specific heat of stainless steel, it is possible to correlate the data, revealing the relationship between the energy density and the resistivity shown in figure 4.41.

![Figure 4.41, Relative increase in resistivity compared to room temperature resistivity from 0 K to 1200 K. A model found in literature [51] predicts the resistivity as a function of the temperature as:

\[ \rho(T) = a \cdot T^b + c \]

where \( a \) is 154.1, \( b \) is 0.0997 and \( c \) is -191; The above model is only accurate between 273 K and 1200 K. If the temperature range is outside these limits the model no longer fits the experimental data as seen in figure 4.42.
Figure 4.42, Model extended beyond its operating boundary, no longer matches data.

To obtain a better fit, the experimental data was interpolated using a Bspline curve fitting technique. The change in resistivity was then modelled more accurately as shown in figure 4.43.

Figure 4.43, Interpolated fit to experimental data. Curve now fitted to the full range of experimental data.

From the change in resistivity it was clear that the steel should only be allowed to reach a maximum of 70% of its melting temperature of 1450 K. Therefore the maximum temperature the steel can achieve during a discharge was set to ~1000 K,
equating to a maximum specific energy density of ~600 kJ/kg. According to the resistivity profile of figure 4.44, this should still increase the resistivity by about 45% from the room temperature value, giving a significant change in resistance.

![Resistivity ratio variation with changing specific energy density, room and melt temperature indicated.](image)

The proposed damping section had the dimensions:

Length: 0.6 m, width: 0.6 m, and thickness: 100 µm

and was designed to have 8 mΩ resistance at room temperature, which increases to 12 mΩ at 1000 K (equivalent to 600 kJ/kg) as shown in figure 4.45.
A second damping section was also modelled which was of the same shape but 140 µm thick. This would have the immediate effect of reducing the room temperature resistance (figure 4.46), resulting in a larger peak current. However it would also lead to a larger magnitude voltage reversals on the capacitor.

Figure 4.46, Change in resistance of a 140 µm thick foil with specific energy.

Figure 4.47 shows the simulated (qualitative) performance of the 2 damping sections identified in figures 4.45 and 4.46.
Considering the information shown, the 100 µm thick section is used as it produces a more suitable current pulse with the loss in the peak current only being about 5% between the two traces shown in figure 4.47.

So far the modelling carried out was based only on simple material data. Significantly more research is required to obtain a more conclusive description of the performance of these damping sections. In addition to stainless steel, the performance of other candidate materials can also be investigated.

For the purposes of this work, the most effective damping section is derived as a compromise between the total material (mass which can absorb the deposited energy) and the initial room temperature resistance of that section. This balance is necessary so that the largest resistance change is realised whilst the section remains in its solid state throughout the discharge. This is achieved by setting a limit to the upper energy density (and therefore temperature) the material should achieve during its operation.
4.4.5 Stainless steel performance

The results in figures 4.48 – 4.51 provide an indication as to how well the steel section performs. The current pulse is measured by a pair of probes built into the lower stripline on the QUATTRO bank. These ‘tunnel probes’ were described in chapter 6.

Figure 4.48, Modelled damped current pulse using 100 µm steel section.

Figure 4.48 is for an initial capacitor voltage of 15 kV on a 210 µF capacitor bank resulting in a peak current of 725kA.

Figure 4.49 – Modelled specific energy density of steel damper (100 µm thick).
Figure 4.50 shows the modelled variation of the internal energy density of the material during the current pulse. It is clear that the material reaches 270 kJ/kg (significantly lower than the 600 kJ/kg limit set), ensuring that it will not melt.

![Graph showing relative resistance increase over time.](image)

*Figure 4.50, Modelled resistivity of the damping section curing discharge.*

The resistivity of the damping section is increased by 20% relative to its original room temperature resistance, which is sufficient to achieve the damped discharge shown in figure 4.48.

![Graph showing specific energy density versus temperature.](image)

*Fig 4.51, Modelled temperature variation with specific energy of the steel section.*
Using the above graph and the peak energy density of 270kJ/kg (figure 4.51), the peak temperature reached by the steel section is found to be 530K. This shows that the material stays well within the limits set, in that it only reaches 33% of its melt temperature in this particular experimental arrangement.

The modelling of the damping section shows that it is possible to plan and carry out experiments on both AMPERE and QUATTRO with a good level of understanding of the performance prior to the shot. The motion of the flyer was also modelled and this is covered in the next chapter.
CHAPTER 5

Flyer-plate experiments and modelling flyer motion

This chapter covers the changes made to the model described in chapter 4, to include motion of the flyer. The additions are explained and the underlying assumptions and justifications clarified.

*It should be noted that some of the graphs in this chapter have been normalised to maintain the classification of the thesis at a lower level.*

Once the electrical performance was satisfactorily modelled (figure 4.18) the model was extended to include the motion of the flyer. The flyer is modelled as a 1D rigid plate and a single bulk velocity is assumed. The motion is determined by calculating the net force on the flyer and the associated displacement. To introduce the flyer plate into the model, the experimental arrangement needs to be well understood. To provide this, the target to be impacted is held a known distance above the flyer as shown in figure 5.1.

![Figure 5.1 – Experimental arrangement showing the flyer, the target holder and the target held in position.](image)

Figure 5.2 shows a cross sectional view of the target holder and flyer section of the stripline. It shows clearly the top and return conductor spacing reducing from 2 cm to 2 mm ensuring that the flyer section experiences the largest accelerating force.
To obtain an accurate model of the motion of the flyer all the necessary forces acting on the flyer need to be considered, these are the aerodynamic drag, the electromagnetic force, the effect of gravity and the compression of the air above the target. It was found that the effect of gravity was negligible compared to the other forces involved and so was omitted from the calculations.

5.1 Modelling assumptions

The following assumptions were made in developing the model in chapter 4:

1) The current flow through the stripline is uniform across the width of the conductor and, due to the symmetrical geometry; it was assumed that the current flows similarly back through the return conductor.

2) The flyer plate is sufficiently thin for the current to flow uniformly through the full thickness of the material and there is no skin effect. The flyer is considered to be the centre section if the 30 cm long flyer foil (figure 5.2) clamped at each end.

3) The only force accelerating the flyer towards the target is the normal component of the Lorentz force.
4) The flyer moves as a single sheet and only a single bulk velocity needs to be calculated (the 1D model neglects edge effect and the clamped edges are sufficiently far from the region of interest so do not affect the results).

5) The flyer does not reach its melting temperature and remains solid throughout the acceleration phase.

6) Deceleration of the flyer is caused primarily by the adiabatic compression of the gas between the target and the flyer, with minor contributions from the drag.

7) The flyer never actually makes physical contact with the target, the impulse is transferred to the target via the compressed air cushion between the target and flyer plate.

Throughout this chapter and the rest of the thesis the definition of the flyer “hitting” the target refers to the moment when the flyer comes to a stop due to the retarding force of the compressed air.

Assumptions similar to those stated above were used in the past for comparable experiments [52].

5.2 Accelerating forces

This section gives details of each of the accelerating forces and describes the relative importance of each during the discharge of the capacitor bank.

5.2.1 Electromagnetic accelerating force

Assuming infinitely long filaments (in the Oz axis) the simplified Biot-Savart law can be used; figure 5.3 is a schematic representation showing the magnetic field generated by a wire carrying current (directed out of the page).
Figure 5.3, Schematic representation of a conductor carrying current and an associated magnetic field line.

The law states that the magnitude of the magnetic flux density, perpendicular to the radius vector at a given point (P) is given by:

$$ |B_p| = \frac{\mu_0 I}{2\pi r_p} $$

for infinitely long wires  \hspace{1cm} (5.1)

where $I$ is the current in the wire and $r_p$ is the radial distance between the wire and the point of interest.

The force on a current carrying conductor (with a linear current density $J$) due to the magnetic field ($B$) is calculated using the standard expression (see section 1.1.2):

$$ F = J \times B $$

\hspace{1cm} (5.2)

The force on the flyer can be calculated using equation (5.3), the complete derivation of this force is given in Appendix G.

$$ |F_y(d)| = \int_0^w |dF_y| \, dx = \frac{\mu_0 I^2}{2\pi w^2} \left[ 2w tan^{-1} \left( \frac{w}{d} \right) - d \ln \left( \frac{d^2 + w^2}{d^2} \right) \right] $$

\hspace{1cm} (5.3)

where $d$ is the separation between the flyer and the stator.

Equation (5.3) is an accurate formula for the total force as it incorporates the
separation of the conductors rather than using the magnetic pressure to estimate the force as used in the past. Equation (5.4) [53] shows the expression used to determine the forces from the magnetic pressure.

\[
|F_y| = \frac{(2B^2)}{2\mu_0} lw = \frac{\left(\frac{2\mu_0 I}{2w}\right)^2}{2\mu_0} lw = \mu_0 \frac{I^2 I}{2w},
\]  

(5.4)

from which it is clear that the force calculated using the magnetic pressure is independent of the separation of the flyer and stator and so remains constant (for a constant current) during acceleration.

Apart from the electromagnetically produced force, the flyer dynamics are influenced by (at least) three other forces, all acting against the EM produced flyer acceleration, as described below.

5.2.2 Aerodynamic drag

Calculation of the aerodynamic drag on the flyer is approximated by using the coefficient of drag for a square plate. This force is caused by friction with the ambient gas (atmospheric air in the present experiments), and is expressed as:

\[
F_{Drag}(v) = \frac{1}{2}\rho_{gas} v^2 C_{drag} lw,
\]

(5.5)

as can be found in any standard text book. In equation (5.22), \(\rho_{gas}\) is the gas density and \(v\) is the flyer velocity. The drag coefficient for the flyer plate (\(C_{drag}\)) is approximately 1.28, the value for a square plate. As evident, this force will be very small for low velocity flyer motion, but will become quite substantial at higher velocities.

5.2.3 Gravity

The third force acting on the flyer is the constant gravitational force:
\[ G = m_{flyer} \cdot g, \]  

(5.6)

where \( m_{flyer} \) is the flyer mass and \( g \) is the gravitational constant. Due to the low mass this force is very small and negligible in comparison to the other forces involved; it is therefore excluded from the model.

### 5.2.4 Adiabatic compression of air

This fourth force is a result of the flyer moving towards a fixed target positioned a certain distance above the flyer. A complete description of all the processes involved is complex and for this work, a simplified representation was adopted.

During a shot, two phases in the flyer dynamics are identified, related to the flyer-target interaction. These are the compression and subsequent decompression of the gas volume, as illustrated in figure 5.6a and 5.6b. For simplicity, an adiabatic compression process is assumed [54] to estimate the retarding force on the flyer.

Adiabatic approximation assumes the air between the flyer and the target cannot escape during acceleration of the flyer and is compressed with the temperature remaining constant. Once the force due to the air compression overcomes the EM force; the flyer reverses direction. The adiabatic approximations given in equations (5.7) and (5.8) have been used for similar work in the past [54, 55].

![Figure 5.6a, Diagram of experimental arrangement prior to the current pulse.](image-url)
Figures 5.6a and 5.6b show the effect of the flyer motion on the volume of gas between the flyer and the target, with the pressure in the reduced volume being calculated from:

$$P_1 \cdot V_1^\gamma = P_2 \cdot V_2^\gamma,$$  \hspace{1cm} (5.7)

as

$$P_2 = \frac{P_1 \cdot V_1^\gamma}{V_2^\gamma},$$  \hspace{1cm} (5.8)

where $\gamma$ is the adiabatic gas constant assumed to be 1.4; the standard value for a pure diatomic gas, and as the majority of the atmosphere is composed of nitrogen, this assumption is valid.

Once the pressure is determined the retarding force is simply the product of the pressure and the area of the target ($Area_T$) it is acting on.

$$F_{Comp} = \left[\frac{P_1 \cdot V_1^\gamma}{V_2^\gamma}\right] \cdot Area_T$$  \hspace{1cm} (5.9)
5.2.5 Net force calculation

The forces described in the previous sections are combined to determine the net force on the flyer during the discharge. Taking into account the remaining forces, with the effects due to gravity being neglected, the differential equations of motion can be written as:

\[
\frac{dv}{dt} = \frac{1}{m_{\text{flyer}}} (F_{EM} - F_{DRAG} - F_{COMP})
\] (5.10)

\[
\frac{dy}{dt} = v
\] (5.11)

The flyer begins to move from its initial position only when \( F_{EM} > F_{DRAG} + F_{COMP} \). The incorporation of equations (5.10) and (5.11) into the extended model is shown in the next section.

5.3 Changes made to model

The changes necessary to include motion of the flyer plate in the model are explained below, together with predicted results from the model. Measurements of the flyer motion are also presented to illustrate the accuracy of the predictions.
5.3.1 – Updated differential solver

The latest iteration of the differential solver is shown below:

<table>
<thead>
<tr>
<th>Total Current</th>
<th>Specific Energy deposited in fuse</th>
<th>Specific Energy deposited in flyer</th>
<th>Net Force Expression</th>
<th>Displacement</th>
</tr>
</thead>
</table>

*MathCAD solver with the addition of the net force (equation(5.10))

This is an extended version of the solver shown in section 4.3.2, and the terms have the same definitions. Here the last two lines determine the net force which is dependant on the total current ($y_0+y_4$), the separation between the stator and the flyer ($y_6$) and also the velocity of the flyer plate ($y_5$).

The force expressions described in sections 5.2.1 – 5.2.4 are independently plotted in figure 5.7. The change in the magnitude of each of these during the current pulse allows a direct comparison between the pressures that they exert on the flyer, enabling the motion of the flyer to be easily understood.

The modelled results shown in figures 5.7- 5.8 are for an arrangement with the following parameters:

- Charging voltage: 37 kV
- EFDR width: 15 cm
- $I_{\text{max}}$: $\sim 450$ kA
Figure 5.7, Modelled current pulse for the parameters given above.

The resulting pressure exerted on the flyer plate (9 cm x 9 cm) due to the forces generated is shown in figure 5.8.

Figure 5.8, Modelled EM pressure due to current and the net force considering all the forces.

As is evident from figure 5.8, the EM force generated initially dominates until just before the first current zero, when the retarding forces ramp up and exceed the EM
force. This causes the flyer to stop and reverse in direction. The individual forces on
the flyer during the discharge are plotted in figure 5.9.

\[ \text{Figure 5.9, Modelled log plot of the three main forces acting on the flyer the model is}
\text{only valid until the flyer comes to a stop (i.e. once flyer “hits” the target).} \]

Figure 5.9 shows the values of the forces and establishes when the compressive
force overcomes the EM accelerating force and the direction of the flyer motion
changes.

An additional benefit of the EFDR is that it allows the EM pressure to decrease
significantly as the current ceases to flow through the flyer, as evident in figure 5.8.
This prevents the occurrence of re-strikes, which is when the flyer repeatedly strikes
the target during the subsequent peaks of the ringing discharge.

In the experimental configuration used here, it is possible to obtain two different
scenarios:

1. a single ‘slap’ which is achieved by having the flyer moving inertially, i.e. no
EM forces acting on the flyer at the moment of impact.
2. Configured to yield what is known as the ‘slap and push’ effect where there is current flowing at and after the initial ‘impact’, causing the flyer to be pushed into the target.

The various experimental arrangements and preliminary results are presented below.

5.4 Flyer motion

Various options were considered when setting up the flyer, the first of which was to use a small coupon-size flyer (9cm x 9cm x 250µm), which would be held in contact with two stainless steel sections (figure 5.10). The logic was that the large current would ensure that a good electrical contact was made and maintained throughout the discharge, by a number of arcs between the static electrode and the flyer.

![Figure 5.10, a) Initial flyer assembly, with flyer held between two steel plates, b) Flyer in an elevated position, indicating potential motion.](image)

During a few initial trial shots it was noticed that there was substantial arcing and marking on the flyer surface, indicating that the current was not uniformly distributed across the width of the flyer as evident in figure 5.11, leading to a non-uniform flyer performance.
A first attempt to overcome this was to install very thin (10 micron) sacrificial foils to make better contact with the flyer, as shown in figure 5.12. Shots then carried out showed much more uniform arcing on the flyer (figure 5.13), indicating a more uniform current distribution and therefore a more uniform acceleration than that achieved by the flyer in figure 5.11.
Following a meeting with a group who had worked on the original foil slap at AWE in the 1980’s [2], it was suggested a longer flyer, clamped at both ends should be used instead. The sound speed in aluminium, the short time duration of the flyer acceleration and the distance from the clamps to the section of the flyer which impacts the target, ensure that the motion of this section is unaffected by the clamps. This method also ensures that the current distribution is as uniform as possible. Results from the first test conducted using this method are shown in figure 5.14. It will be seen that the clamped ends are sufficiently far from the centre of the flyer such that their effects can be neglected and 1D planar motion can be assumed.

Figure 5.14, Aluminium flyer clamped at both ends shown before and after the discharge.

Figure 5.14 shows the flyer plate before and after a shot, with the flyer deformation due to its motion being evident. The sections not impeded by the target are free to move further whereas the motion of those below the target is limited, leading to the deformed shape which can be seen. The fibre-optic system used to monitor the motion of the flyer plate has been developed by the Radiation science team at AWE the five probes can be seen in the centre of figure 5.14. Ideally all five probes should register identical motion to indicate uniform acceleration of the flyer. Details of the various diagnostics used are provided in chapter 6.
Initial results from the model predicted higher peak velocities than were measured (see section 5.4.1). It was initially thought that the flyer was being slowed down by the material having to stretch to reach the target and a term to account for the energy loss due to stretching could be added to the model.

Before this was attempted however, a series of tests were carried out with additional material added to the flyer in the form of the small arches shown in figure 5.15. These provide the additional material necessary so that the flyer would not need to stretch to reach the target. The new arrangement made no difference and the measured velocity was still lower than the expected value.

![Figure 5.15, Diagram showing one of the pre-kinked flyer designs.]

The following section gives a brief overview of the experimental results and also identifies the key source of the loss in peak velocity.

5.4.1 – Experimental results

Imparting the required impulse to the target requires the impact to be as uniform as possible and the flyer plate must therefore remain flat as it approaches the target. The shots carried out to date show that it is possible to obtain highly reproducible shots. Figure 5.16 is a comparison of 3 separate experiments with the same initial parameters. It is clear to see the high degree of repeatability between shots and highlights the shot to shot reproducibility of the AMPERE Foil Slap facility.
Figure 5.16, Measured data for three shots with the same initial conditions.

There is however a consistent difference between the measured and modelled velocity results as seen in figure 5.17.

Figure 5.17 shows that the measured velocity is lower than the modelled velocity and also that the flyer is not accelerated uniformly, as all four probes do not reach the target simultaneously.

The data in figure 5.17 is for a shot with the bank charged to 25 kV with an aluminium fuse 50 µm thick, 30 cm long and 8.6 cm wide, producing a maximum current of 300 kA. The target was mounted 2 mm above the initial flyer position. The results indicate that the flyer plate tilts as it accelerates; causing probes 1 and 2
to decelerate and come to a halt before probes 3 and 4. This effect becomes less noticeable at higher energies (and therefore higher velocities) as evident in figure 5.18.

The results in figure 5.18 are for a flyer which achieved a higher maximum velocity than that in figure 5.17. The bank was charged to 29.5 kV, with an EFDR width of 10.2 cm; achieving a maximum current of 360 kA. As the flyer is moving faster, less gas can escape, making the assumption of an adiabatic compression more realistic. As expected, all the probe outputs are in close agreement, indicating a more uniform acceleration of the flyer; however the peak measured velocity still falls short of the predicted value.

![Figure 5.18, Measured flyer velocity compared to modelled value.](image)

In all the shots carried out, the measured foil velocity profile resembles that of the model, implying that the gas compression model (the major contribution to the deceleration of the flyer) is working as expected. However, as the model overestimates the peak velocity, other aspects need to be considered to provide an improved representation of the flyer performance. It was concluded that an additional retarding force may have been inadvertently omitted at this stage and needs to be introduced into the model.
Various processes were considered and discarded; until careful investigation highlighted a realistic source for the discrepancy between the modelled and measured peak velocities. This was the voltage drop on the bank between isolation of the charging power supply and triggering the switch, as described below.

### 5.4.2 Capacitor bank voltage prior to discharge

A series of simple charge, isolate and dump experiments were carried out whilst directly measuring the voltage on the capacitors to better estimate the voltage on the bank at the moment of triggering the discharge. During normal operation of the facility there is a 6 second delay built into the system between isolating the HV power supply (1 second) and triggering the switch (5 seconds). The experiments discussed here were designed to identify the voltage drop on the bank during the 6 second prior to triggering the switch. This was achieved by connecting a HV probe between the top plate of the switch and the ground of one of the capacitors.

An oscilloscope connected to the voltage probe was set with sufficient pre-trigger to capture the 20 seconds prior to the discharge and to trigger on the falling edge. After the capacitor was charged to the desired voltage, it was left isolated for 15 seconds before being triggered. The capacitor voltage was captured, including the initial voltage as well as the subsequent voltage decay and finally the drop to zero when the bank was fired.

The 2000:1 voltage probe used is shown in figure 5.19; and is the same probe used to measure the voltage across the EFDR.
Figure 5.19, Northstar 2000:1 voltage probe, to measure bank and EFDR voltage.

Figure 5.20 shows the decay in the capacitor voltage for a number of initial charging voltages. As can be seen there is an appreciable drop in the 15 second isolation period.

**Figure 5.20, Measured voltage decay for various nominal charging voltages, followed by a 15 second isolation period.**
Figure 5.20 clearly identifies the drop in voltage as one contributor to the discrepancy in the velocity trace, as the reduced bank voltage would inevitably lead to a lower peak velocity.

**5.4.3 Effect of capacitor bank bleeding**

It is possible to determine from figure 5.20 that there is approximately a 6% voltage drop over the 15 second isolation period. During normal operation of the facility there is a 6 second delay between the end of charging and the moment the switch is triggered. Assuming a linear decay in figure 5.20, a 2.2% voltage drop on the bank can be assumed between isolating and triggering the system; with the effect of this on the performance of the model being evident from figure 5.21.

![Figure 5.21](image)

*Figure 5.21, Measured data taken from figure 5.18, compared to the reduced voltage modelled velocity trace.*

Figure 5.21 shows the predicted velocity of the flyer with the initial voltage reduced by 2.2%, and as seen there is some improvement with the peak velocity closer to the measured value and the impact occurring closer to the actual measured data.

The next change made was to modify the force expression, since the approximations used are not 100% accurate and this is an area where a large error can be
introduced by oversimplifying the processes involved. There may also be an entire aspect of the physics which has not yet been considered during the acceleration of the flyer.

### 5.4.4 Model correction and results

Initially equation (5.20) was adjusted and the value of the current reduced by 3%. This gives a total drop in the EM force of 5.9% and yields a more accurate velocity profile. The results obtained with this correction are shown in figure 5.22 - 5.25 for different initial conditions.

![Figure 5.22, Corrected model; with a charging voltage of 21.5 kV and an EFDR width of 8.5 cm, measured and modelled data.](image)

*Figure 5.22, Corrected model; with a charging voltage of 21.5 kV and an EFDR width of 8.5 cm, measured and modelled data.*
Figure 5.23, Corrected model predicting performance of higher velocity shot. Charging voltage of 23.5 kV with an EFDR width of 8.1 cm.

Figure 5.24, Modelled and measured results. Capacitor bank nominally charged to 29.5 kV with a 10.2 cm fuse.
The above figures show that the performance of the flyer with the empirical correction produces results which are in agreement with the experimental data for a range of initial parameters. The model can now be used to confidently predict the performance of the flyer plate and to plan future shots.

The reduction in the force which has been introduced can be attributed to 2 or 3D interactions between current filaments. Due to the 1D nature of this model it is beyond the scope of its capabilities. This reduction may be better understood with the development of a more complex 2D or 3D model as part of follow on work to this research.

### 5.4.5 Magnitude of forces during discharge

To assist in understanding the behaviour during these experiments the individual forces can be plotted and compared on the same axes. Figure 5.26 shows how the three major forces change during the current pulse.

As can be seen, the EM force is dominant due to the rapid initial rise in current. As the discharge reaches the first zero the flyer has moved considerably and has compressed the gas between the flyer and the target. As the flyer continues to move and compress the gas, the resulting force on the flyer increases rapidly and quickly becomes dominant (black dashed line), causing the flyer to change direction. During
this time the force due to the aerodynamic drag also changes and can be seen to increase and decrease in relation to the velocity of the flyer.

![Graph showing the force over time.](image)

**Figure 5.26, Closer look at the first period of the discharge (model only valid until the peak compressive force).**

It should be noted that the model described is only valid until the flyer comes to a halt for the first time, after which point the 1D model assumes an elastic collision with the target which is incorrect. Figure 5.26 uses a logarithmic scale in the Y-axis and provides an indication of the dominance of the various forces at different times during the discharge.

An additional feature to note is that the direction of the current does not affect the EM force, as highlighted in figure 5.27. The solid line shows the current trace and the dashed line is the corresponding EM force associated with that discharge.

![Graph showing EM force over time.](image)

**Figure 5.27, EM force resulting from an oscillatory discharge.**
As every peak will produce a large EM force, this once again reinforces the need to have a single peak in the discharge to deliver the most well defined impulse to the target.

5.4.6 Flyer displacement

The results in this chapter have shown that the model developed is capable of determining the pre target impact velocity of the flyer plate as well as accurately modelling the current pulse for various initial conditions. The velocity trace can in turn be integrated to obtain the displacement of the flyer which can be used to confirm the initial target height as shown in figure 5.28.

Figure 5.28, Modelled displacement of flyer plate.

Figure 5.28 shows that this particular target was set 2 mm away from the flyer. The experimental velocity traces can be integrated to determine the actual displacement of the flyer; the calculated displacements from the velocity traces in figure 5.22 are shown below compared to the optimal modelled displacement:
Figure 5.29 shows that the flyer displacement is slightly larger than the initial 2 mm (~2.1 mm). The reason being, that the target is pushed back by the significant pressures exerted on it. As it is only held in place by a few grub screws, it is feasible that it is pushed into the holder during the flyer acceleration leading to a larger than expected flyer displacement.

This and the preceding chapters have covered the development and performance of the 1D model to simulate the electrical and mechanical performance of the flyer plate system. It has been shown that using empirically derived correction factors, the model can accurately determine the performance of the flyer motion as well as the electrical performance of the bank and the EFDR. Chapter 6 reviews the various standard and bespoke diagnostics used during the research.
CHAPTER 6

Pre-existing diagnostic techniques

The work presented in this thesis utilised many standard diagnostics such as voltage probes and current monitors (Rogowski coils and Pearson current monitors), as well as a range of more specialised diagnostics such as high-speed photography, in-situ inductive current monitors, interferometric diagnostics and carbon pressure gauges, together with CCTV systems to monitor the experimental area. The diagnostics are briefly covered in this chapter with the benefits of the various techniques being highlighted.

6.1 – Standard diagnostics

This chapter highlights the various diagnostics and the way they were utilised on both AMPERE and QUATTRO. To obtain useful information from the experiments, the current pulse, the induced voltage across the stripline conductors, the charging voltage of the bank, the velocity of the flyer as well as the overall state of the experimental assembly pre and post shot all needed to be monitored.

For any high current bank, there are certain standard diagnostics which are employed; in particular these are voltage and current monitors. On AMPERE the current is measured using two separate systems, the first being a bespoke Rogowski coil designed to operate at a peak current of 600 kA and calibrated using a factory certified Pearson current monitor. It was initially thought that the Rogowski coil was giving a slightly higher current reading than was expected, leading to the higher predicted velocities seen in figure 5.17, however this velocity discrepancy was later attributed to other losses as described in sections 5.4.3 and 5.4.4.

The standard diagnostics used during this research are all described in detail in Appendix H.
This chapter has introduced a number of standard diagnostic techniques. However in order to understand the current distribution in the stripline a novel diagnostic needs to be developed. This novel diagnostic technique is covered in chapters 7 and 8.
Chapter 7

Initial development and calibration of novel sensor

This chapter covers the development of a novel inductive probe, which has been shown to be capable of detecting the location and magnitude of localised currents. The technique is shown to work at low voltage as a proof of principle and the experiments conducted are described in this chapter.

7.1 Background

A novel sensor has been proposed as a means of measuring the current distribution in thin, wide transmission lines. The sensor is termed MIDOT, as it is based on both the mutual inductance \( M \) and the rate-of-change of current \( I-Dot \) in the system. At this stage some preliminary proof of principle tests and the theory underpinning the technique are described. It is however envisaged that further development of this technology may lead to the possibility of measuring the current distribution in wide, continuous, close coupled transmission lines.

Figure 7.1 gives an idea of how the current in wide transmission conductors can be distributed. At present there is no well established method of determining where the current flows in such conductors and it is the aim of this chapter to develop a novel sensor to achieve this.

![Figure 7.1, Stripline conductors with (a) uniform current distribution and (b) distribution highlighting the edge and skin effect.](image-url)
In figure 7.1 (a) it is assumed that the current is uniformly distributed across the conductor (as assumed in the 1D model of chapter 4), whereas figure 7.1 (b) shows the current concentrated at the edges and inner surfaces [63]. This non-uniformity of the current flow leads to a non-uniform force distribution and therefore a non-planar acceleration of the conductors.

One crucial assumption throughout this work and in all the previously discussed modelling, is that the current distribution in the upper and lower conductors is identically i.e. mirrored, as shown in figure 7.2. This allows symmetry of the arrangement to be exploited which reduces the computational requirements and makes it much easier to model and understand.

![Figure 7.2, Cross section of stripline showing mirrored current flow in upper and lower stripline conductors.](image)

**7.2 Filamentary model overview**

The well-established 2D filamentary model [35], breaks the large conductors into many smaller filaments, as shown in figure 7.3. It was believed that an extension of this method could be used to investigate the current distribution in the conductors experimentally.
The model developed is based on a simple LCR circuit fed into a stripline, with the stripline conductors modelled as shown in figure 7.4:

\[
M_{ij} = \frac{\mu_0}{2\pi} \left( \ln \frac{l + \sqrt{l^2 + \text{dist}_{ij}^2}}{\text{dist}_{ij}} - \frac{\sqrt{l^2 + \text{dist}_{ij}^2}}{l} + \frac{\text{dist}_{ij}}{l} \right),
\]

(7.1)
Equation (7.1) is for any two equal length, straight parallel wires (i and j) of circular cross section. The separation between their cross section centres is $\text{dist}_{i,j}$ and $l$ is the length of the filaments.

Due to the shape of the stripline, the filaments in the model are rectangular and not circular, and for a wide, thin transmission line, these filaments are used as indicated in figure 7.5.

![Figure 7.5, Rectangular cross-sections of two asymmetrically positioned parallel filaments.](image)

Figure 7.5 shows the separation between the centres of the cross sections of each filament ($d_{ij}$). Since the filaments of the the computer model are neither circular nor square, the geometric mean distance (GMD) is used to determine the effective filament separation rather than the geometric distance between their cross section centres. The expressions required to determine the GMD [65] are used in the 2D model; however the development and use of the 2D model is not within the scope of this thesis.

### 7.3 Modelled effects of current distribution

Using the 2D model developed at Loughborough University [35], the motion of the flyer resulting from a specific current distribution can be predicted.
7.3.1 Flyer 2-D dynamics

The flyer is divided into a number of equal filaments; with each column of filaments capable of moving independently (figure 7.6). This allows the flyer deformation to be modelled [66] and is justified by the very rapid vertical flyer acceleration due to the application of a high current density, and the subsequent high vertical velocity compared to the lateral sound speed in the metal.

Figure 7.6, (Left) Indicative magnitude of the force acting on each filamentary column at \( t=0 \), (Right) Filamentary representation of 2D conductor dynamics during a current pulse.

The force distribution of figure 7.6 shows what happens when the current in the flyer increases towards the edge. Once the electromagnetic forces acting on the columns are calculated, the column dynamics can be determined using standard expressions.

7.3.2 2D model predictions

The main results obtained using 2D modelling are shown in figure 7.7 – 7.10. The results provide considerable useful information, both from the point of view of a designer trying to maintain a flat flyer surface and also allowing a clear understanding and interpretation of data obtained from the various diagnostic tools used, such as heterodyne velocimetry techniques or ultrahigh speed cameras.
Figure 7.8, shows a typical high current discharge with four points in time identified by the letters a, b, c and d. Both measured and modelled current data is shown and as can be seen the two traces almost overlap perfectly, which gives good confidence in the computer model.

![Figure 7.7, Current trace for a typical high current discharge.](image)

Figures 7.8 and 7.9 show the calculated current distribution across the cross section of the flyer plate at the times indicated in figure 7.7.

In this particular case the flyer conductor was 9 cm wide ($w$) and 250 µm thick ($th$).

![Figure 7.8, Evolution of current distribution prior to peak current; a) 5 µs after $t_0$, and b) 15 µs after $t_0$.](image)
It is clear that the current is initially greatest on the inner face of the stripline (the face closest to the return conductor) and that the current at the edge of the flyer is slightly higher than at the centre. This variation of the current across the width can lead to some variation in the flyer performance; it is also possible to see the diffusion of the current through the thickness of the conductor. It is clear that the current has become more uniformly distributed through the conductor by the time of the peak current.

Figure 7.9, Evolution of current distribution after peak current; c) at 25 µs after $t_0$, and d) ~30 µs after $t_0$.

At time d, the current is going through the zero point, and as seen the current changes direction on the inner face first, with this diffusing through to the full thickness after a few time steps. The current in each column of filaments can be used to determine the vertical velocity of that column. Figure 7.10 shows the modelled velocity for each of the columns in one-half of the conductor. The majority of the traces are in agreement; this is to be expected as the current in the majority of the filaments is uniform. The column at the edge of the flyer shows a different velocity profile, which is directly related to the different current flow in the filaments making up that column.
Figure 7.10, Modelled velocity of each column of filaments and the measured velocity from the centre of the flyer.

The effect of the current distribution can be seen by modelling the flyer deformation during the discharge; changes to the displacement and shape of the cross section allow this effect to be appreciated. This is evident from figure 7.11, which shows that having a non-uniform current distribution leads to non-planar flyer acceleration. This in-turn will lead to a non-uniform impulse on the target; which is undesirable when simulating cold x-ray effects. This further enforces the need to know the current distribution in the actual foil flyer strip-lines.

Figure 7.11, modelled flyer cross section geometry at different moments during the acceleration, t1=20µs, t2=30µs, and t3=40µs.
7.4 MIDOT sensor arrangement

Figure 7.12 shows the basis for the sensor developed which can monitor the current distribution in a flat transmission line. The series of sensor filaments (independent of the experimental circuit and each other) positioned above the top conductor of the stripline are all inductively coupled to the filaments of that conductor.

![Diagram of sensor filaments and flyer plate conductor](image1)

*Figure 7.12, Proposed sensors installed above the flyer plate conductor.*

As all the parallel filaments are inductively coupled, any current flowing through the flyer-plate circuit will induce a voltage in the filaments of the proposed sensor. The measured voltage in each sensor filament is a summation of contributions from every filament in the flyer plate and return conductor.

![Diagram of inductive coupling](image2)

*Figure 7.13, Proposed sensors installed above the flyer plate conductor.*

To enable the phenomenon to be understood a few assumptions have to be made:
1) Due to the skin depth and proximity effect, a single layer of filaments can be used to represent the upper and lower conductors.

2) It is assumed that the current is evenly distributed through the thickness of the single filament layer i.e. the layer is thinner than or equal to the skin depth.

To further simplify the problem, initial tests using only a single filament pair of the reduced stripline is considered; this can be represented as two vertically aligned, thin parallel wires.

Figure 7.14 shows the reduced problem, composed of only a single filament stripline with the sensor filaments positioned directly above and at positions with slight lateral displacement. Due to this geometry, equation (7.1) can be directly applied to the problem to determine the mutual coupling between the two source filaments and the sensor filament.

The changing current in the source filaments induces a voltage in the sensor filaments proportional to the mutual inductance coupling of the two filaments and the rate of change of current in the source. The total voltage generated in the sensor is a summation of the voltage induced by the upper and lower source filaments. As these currents are in opposite directions, the induced voltages will also be opposed; for a single pair of filaments the measured signal will therefore be:
\[ V_{Total} = \left( M_{upper} \cdot \frac{dI_{upper}}{dt} \right) + \left( M_{lower} \cdot \frac{dI_{lower}}{dt} \right), \]  

(7.2)

where \( M_{upper} \) is the mutual coupling between the sensor and the upper conductor and \( M_{lower} \) is the mutual coupling of the sensor with the lower conductor. Since the same current flows in both conductors, but in opposite directions:

\[ V_{Total} = (M_{upper} - M_{lower}) \cdot \left( \frac{dI}{dt} \right), \]  

(7.3)

It is this partial cancellation of the signal which makes the MIDOT technique a potentially useful current sensor for transmission line geometries. The main feature is that the induced voltage falls very quickly with an increased lateral separation between the source filament pair and the sensor filament. It is precisely this feature that enables the MIDOT technique to be used as a current location sensor.

### 7.5 Initial experiments

The initial experiments carried out were performed with a single, thin filament held under tension, and the return conductor sufficiently far away as to not significantly affect the measured induced signal. A schematic diagram of the arrangement is shown in figure 7.15.

![Figure 7.15, The initial single filament experiment.](image-url)
Initially the source filament and the active part of the MIDOT loop were kept in the same plane. The rest of the MIDOT loop was positioned to ensure the wires were kept parallel and perpendicular, as shown in figure 7.16.

\[ d \] is the separation between the two filaments, \( w \) is the active length of the sensor and \( l \) is the length of the source filament. Initial results only show the coupling between the active part of the sensor and the source filament as indicated above; the effect of the rest of the sensor loop is taken into account as seen in figures 7.22 and 7.26.

The arrangement shown above is with both sensor and source filaments in the same plane, as evident in the side view of the arrangement shown in figure 7.17:

\[ \text{Source filament} \quad \longleftrightarrow \quad \text{Sensor loop} \]

Equation (7.1) is valid for filaments of equal length, but, in the present case, the parallel filaments are of unequal length. Grover [64] has presented the expressions
necessary to determine the corresponding mutual coupling between filaments of unequal length \((m\) and \(n)\) as shown in figure 7.18:

\[
\begin{align*}
\text{Figure 7.18, Arrangement of any two unequal parallel filaments of length } m \text{ and } n.
\end{align*}
\]

Using equation (7.1), and breaking the above case into a series of simpler calculations, the following expression can be generated to determine the net mutual coupling between any two unequal parallel filaments. For the case shown in figure 7.18 the mutual coupling is determined using equation (7.4).

\[
M_{m,n} = \frac{\left( M_{n+p} + M_{m+q} \right) - \left( M_p + M_q \right)}{2},
\]

(7.4)

where the individual terms have the following meanings:

\(M_{m,n}\) is the mutual coupling between the two filaments \(m\) and \(n\).

\(M_{n+p}\) is the mutual coupling of two equal length parallel filaments of length \(n+p\).

\(M_{m+q}\) is the mutual coupling of two equal length parallel filaments of length \(m+q\).

\(M_p\) is the mutual coupling of two equal length parallel filaments of length \(p\).

\(M_q\) is the mutual coupling of two equal length parallel filaments of length \(q\).

If however the filaments are positioned symmetrically, such that \(p=q\), in figure 7.18, then equation (7.4) reduces to:

\[
M_{m,n} = M_{n+p} - M_p,
\]

(7.5)
In the experimental arrangement, the source filaments are of length $L$, and the sensor filament is of length $w$. It then follows that:

$$n + p \equiv w + \frac{L-w}{2}, \quad (7.6)$$

And

$$p \equiv \frac{L-w}{2}, \quad (7.7)$$

and the total mutual coupling of symmetrically positioned sensors is:

$$M_{net} = M \left( w + \frac{L-w}{2}, \text{dist} \right) - M \left( \frac{L-w}{2}, \text{dist} \right). \quad (7.8)$$

Equation (7.1) is used to determine the mutual coupling for filaments of a given length, for the symmetrically positioned filaments of unequal length, equation (7.8) can be used together with equation (7.1) to determine the net mutual coupling for that arrangement.

In the proposed arrangement the filaments can approach each other to a minimum distance between their centres equal to the wire diameter. This can be used to calculate the maximum mutual coupling and to assess how this falls with lateral separation. The experimental arrangement and the results of this are shown in figures 7.19 and 7.20 respectively:

*Figure 7.19, Schematic arrangement of the single filament experiments.*
In the above arrangement, the sensor filament (which will now be referred to as the MIDOT filament) is moved about its initial position as indicated in figure 7.20. The calculated mutual coupling variation due to this for three different vertical separations (between the source and sensor filament) is shown in figure 7.20:

![Figure 7.20](image.png)

*Figure 7.20, Modelled mutual coupling and its change with lateral separation using single filament arrangement.*

The next step is to determine the effect of the return conductor of the MIDOT loop using the arrangement shown in figures 7.16 and 7.17. The induced signal due to the return conductor of the MIDOT will be both lower in magnitude and opposed in direction to that from the sensor filament due to its larger physical separation from the source filament. The experimental configuration used is shown in figure 7.21.
Figure 7.21, experimental arrangement showing the MIDOT and source loop.

The modelled mutual coupling from the arrangement described in figures 7.17 and 7.21 is shown in figure 7.22.

Figure 7.22, Effect of including the MIDOT return on calculated mutual coupling.
In figures 7.20 and 7.22, the source filament is positioned at the origin and the effect of changing the lateral separation by ±10 mm is indicated. Figure 7.22 confirms that the effect of the return conductor of the MIDOT loop cannot be neglected.

Figures 7.23 – 7.25 show the experimental arrangement used for the initial experiments. Figure 7.23 shows the source and MIDOT filaments positioned 5 mm apart. The source filament is held in position using thick copper posts which are fixed into the wooden frame as seen in figure 7.24.

![Figure 7.23, Source and sensor filaments positioned 5 mm apart.](image)

A Pearson current monitor is positioned around the source filament conductor to measure the current flowing through it.

![Figure 7.24, Pearson current monitor installed onto the active source filament.](image)
To aid with the positioning of the MIDOT a series of plastic posts were positioned into the wooden frame, these were spaced 5 mm apart and ensure that the active portion of the MIDOT is always of the same length and is kept parallel to the source filament.

To provide a complete understanding of the interactions between the various conductors, both sets of parallel wires need to be considered, that is the return conductor for the source as well as that for the MIDOT must be taken into account. Tests were performed using a Mylar sheet to increase the vertical separation between the MIDOT plane and the source plane as shown in figure 7.25.

![Experimental arrangement of source and sensor filaments, with the various filament separations identified.](image)

Figure 7.25. *Experimental arrangement of source and sensor filaments, with the various filament separations identified.*

A schematic of the dual plane arrangement (one plane for the MIDOT and one for the source filaments) is shown in figure 7.28. The various separations are identified as well as the positive or negative contribution made to the overall coupling.
It is stated by Grover [64, chapter 7], that the mutual coupling between any two filaments which meet at a point is proportional to the cosine of the angle between them, which in the case of the MIDOT and source filament loop is 90° as shown in figure 7.16. This implies that there will be no mutual coupling between filaments which are at right angles to one another. Figure 7.26 shows the filaments which have a non-zero interaction. As can be seen, four filaments pairs are identified and need to be accounted for to determine the overall mutual coupling.

For symmetrically positioned filaments, as used in this arrangement (see figures 7.16 and 7.21), equation (7.8) should be used together with the vertical separation ($h$ in figure 7.26) to determine the total mutual coupling.

For the case shown in figure 4.26, the vertical separation ($h$) remains constant, and the distances between the filaments are therefore:

$$dist_1 = \left(\sqrt{d^2 + h^2}\right),$$  \hspace{1cm} (7.9)

$$dist_2 = \left(\sqrt{(d + R)^2 + h^2}\right),$$  \hspace{1cm} (7.10)

$$dist_3 = \left(\sqrt{(d + t)^2 + h^2}\right).$$  \hspace{1cm} (7.11)
\[ \text{dist}_4 = \sqrt{(d + R + t)^2 + h^2}, \]  
\[ \text{dist}_4 = \sqrt{(d + R + t)^2 + h^2}, \]  
\[ (7.12) \]

Considering the relative direction of the current flow the net mutual coupling between the 2 sets of parallel filaments is given by:

\[ M_{\text{total}}(\text{dist}) = M_{(\text{dist}_1)} - M_{(\text{dist}_2)} - M_{(\text{dist}_3)} + M_{(\text{dist}_4)}, \]  
\[ (7.13) \]

### 7.6 Experimental data

The current pulse in the source filament obtained from a signal generator had a very well defined flat top pulse with a rise time of \(<100\) ns and a width of \(~600\) ns; as shown in figure 7.27.

![Figure 7.27, Measured source filament current pulse.](image)

This pulse induces a voltage in the MIDOT proportional to the rate-of-change of the current, with the measured signal being shown in figure 7.28.
Equation (7.2) states that

\[ V_{Sensor} = M \frac{dI}{dt}, \]

if this expression is integrated, a signal directly proportional to the current can be obtained,

\[ \int V_{Sensor} = \int_{-\infty}^{\infty} M \frac{dI}{dt} dt = MI, \]

(7.14)

The integrated voltage signal (using MathCAD) is shown in figure 7.29;

Figure 7.28, Induced voltage for zero lateral displacement and 63 µm separation between the filament centres.

Figure 7.29, Integrated signal from the MIDOT.
Figure 7.29 shows a signal proportional to the source filament current pulse. Comparing the source current to the integrated signal and making them of equal magnitude by using a conversion factor allows the mutual inductance to be determined. The factor applied to the signal in figure 7.29 is the experimental measure of the mutual coupling, 220 nH in this particular case; which provides the matched signals shown in figure 7.30.

Figure 7.30, matched source current and processed MIDOT current.

As the separation of the MIDOT sensor and source filament is increased by increasing the lateral displacement, the induced signal is reduced as shown by the measured results in figure 7.31.

Figure 7.31, Voltage from the MIDOT sensor for a range of lateral separations.
The corresponding changes in mutual coupling at these discrete positions can be calculated and the modelled and measured values are compared in figure 7.32.

Figure 7.32, Modelled and ‘measured’ inductive coupling at discrete positions.

Figure 7.32, shows how the mutual coupling changes on both sides of the source filament position, for displacements up to 40 mm.

If this range is increased to 30 cm, it is possible to see that both the modelled and experimental results indicate the effect of the return conductor of the source filament circuit, which is 25 cm away from the zero position. The results in figure 7.33 are measured and calculated at specific positions to provide a good comparison.

Figure 7.33, Modelled and ‘measured’ inductive coupling over a larger separation.
For the single filament arrangement the signal picked up by the MIDOT only drops away significantly after the sensor is ~5 cm away from the source filament. This does not allow sufficient lateral sensitivity for use as a current distribution sensor.

### 7.7 Filamentary stripline geometry

The original (single filament) MIDOT concept can be extended, with the return conductor of the source filament being brought to within 2 mm of the source filament, which is representative of the actual stripline geometries used by flyer-plate facilities. Figure 7.34, shows a schematic of the arrangement of the filaments in this more representative situation.

![Modified stripline arrangement, with the go and return conductors separated by 2 mm.](image)

Expressions similar to equations (7.9) – (7.12) can be used to determine the distances between the four filament pairs in the above configuration, which can be used with equations (7.1) and (7.13), to calculate the mutual coupling between the complete filamentary stripline and the MIDOT.

The experimental stripline was formed from a 1 m long pair of enamelled wires, 63 µm in diameter, fixed to either side of a sheet of polyethylene as shown in figure 7.35.
The separation of the centres of the two filaments is 2.063 mm, shown as $R$ in figure 7.34.

The height ($h$ in figure 7.34) is obtained by the use of a Mylar sheet 250 µm thick, which positions the MIDOT in a plane 250 µm above the upper source filament. Including the thickness of the wires used gives the total separation between the centres of the upper source filament and the MIDOT sensor filament as 313 µm.

The modelled performances of the configurations in figures 7.34 and 7.26 are shown in figure 7.36.

---

**Figure 7.35, Laboratory stripline filament arrangement.**

**Figure 7.36, Comparison between the single filament arrangement and the stripline geometry ($h = 313 \, \mu m$).**
It is clear from the theoretical performance of the sensor that the stripline arrangement produces a signal from which it is much easier to identify the position of the source filament. This is because the signal drops to zero rapidly either side of the source filament pair. Considering a 5 mm lateral displacement of the sensor produces an 80% drop in signal for the stripline configuration whereas for the single force filament this drop is only ~30%.

The experimental and modelled performance of this new arrangement was assessed by conducting a 100 mm sweep either side of the source filament position. The results from this are shown in figure 7.37 and 7.38.

![Figure 7.37, Modelled and measured performance of stripline arrangement.](image)

As evident from figure 7.38, the MIDOT is only sensitive to current flowing within 4 mm on either side, any current flowing further away than does not induce any appreciable voltage in the sensor.
Comparison of figure 7.38 with figure 7.32 shows that the stripline geometry produces a very localised signal.

The two main parameters which affect the performance of the MIDOT are:

1) The vertical height of the MIDOT above the upper source filament ($h$).

The height of the sensor above the source filament changes the peak level of the induced signal, as shown in 7.39. As can be seen the smaller the separation, the larger the peak signals, as expected.
2) The separation between the source filaments ($R$).

Reducing the separation between the upper and lower stripline conductors increases the cancellation between the induced signals from the top and return source filaments; thus leading to the more localised, but lower magnitude signal shown in figure 7.40. In all three cases the MIDOT was positioned 313 µm above the upper stripline conductor (i.e. $h=313$ µm), with the stripline separation ($R$) being changed.
As can be seen the closer the two stripline conductors, the more localised the induced signal becomes, although this is achieved at the expense of a lower peak signal. It is clear that by using an appropriate arrangement of conductors, a resolution of ±1 mm can potentially be achieved. The 2 mm stripline arrangement is used in all the experiments described in this thesis in order to simulate the existing experimental facilities.

To obtain a better understanding of why the signals are so localised, it is useful to consider the difference in the filament separations at zero lateral displacement compared to even 5 mm of lateral displacement. Figure 7.41 illustrates these two arrangements.

![Figure 7.41, Arrangement of MIDOT at 2 locations A) At zero lateral displacement, and B) 5 mm lateral displacement.](image)

The “path difference” between sensor A and each of the stripline conductors is 2063 µm; this difference allows for a significantly different induced voltage from each of the source conductors. For sensor B, the corresponding difference is much smaller at 526 µm, and as such yield to a much lower net signal. If the lateral displacement (of sensor B) is reduced to 4 mm, the path difference becomes 600 µm, at 3 mm, it is 810 µm and at 2 mm it becomes 1081 µm.
The smaller this difference the more the signals cancel and for equidistant sensors, this would produce MIDOT voltages of equal magnitude but opposite sign, leading to zero net signal. Figure 7.42 shows how the value of the path difference \((\text{dist}_2 - \text{dist}_1)\) changes as the lateral displacement varies for two different cases; case 1, where there is a 2 mm insulator between the source conductor pair and case 2, where there is no additional insulator between the source conductors.

![Figure 7.42, variation of the path difference (dist2 – dist1), with increasing lateral separation. Path difference is shown on a log scale for clarity.](image)

As can be seen from figure 7.42, the best resolution is obtained with minimal stripline insulation. The data presented in figure 7.42 is on a log scale for clarity and as seen case 2 has a much sharper drop in signal strength due to the path differences converging more quickly with increasing lateral separation. The information presented confirms that the MIDOT technique is a good candidate for use as a current location sensor. It can locate the source current to an accuracy of a few mm in a thin stripline configuration.
Considering the positional sensitivity of the experimental configuration it is feasible to assume that regardless of the magnitude of the current, each MIDOT sensor will only produce an appreciable signal due to current flowing within ±2 mm of its location.

As stated above, the accuracy and resolution of the MIDOT system can be improved by changing the stripline separation and/or vertical height of the MIDOT. However, the arrangement used here needs to mirror the experimental facilities which have already been created at AWE and Loughborough University, and provide an analogue of the existing facilities on which to optimise the technique.

### 7.8 Development of initial MIDOT Array

To obtain a measurement of the current distribution across a wide conductor, a number of MIDOT probes need to be used simultaneously. To achieve this, an array of sensors was assembled allowing signals from different lateral positions to be captured on the same discharge.

To ensure there is no cross talk between adjacent MIDOT sensors in the array, an experiment to test the effect of two adjacent probes was conducted. The main point to note is that each probe was connected to a high impedance voltage probe. This ensures that negligible current flows through the MIDOT conductors and since it is this current that would lead to any secondary inductive effects, it was expected that there would be no cross talk.

To confirm this, an experiment was performed with two MIDOT probes, positioned 10 mm apart, with the source filament pair directly below one of the probes as shown in figure 7.43.
Figure 7.43, Conductor arrangement for testing effect of adjacent MIDOT loops.

MIDOT A was initially an open circuit and the voltage induced in MIDOT A recorded using the high impedance probe. MIDOT B was then changed to form a short circuit (as seen in figure 7.43) and the induced voltage on MIDOT A was captured again. The two signals are shown figure 7.44, and as can be seen they are virtually identical.

Figure 7.44, Measured open-circuit voltage on MIDOT A.

As seen, the results show that the proximity of the adjacent MIDOT sensors does not affect the induced voltage on that sensor. The slight differences seen in figure 7.44
can be attributed to experimental error introduced when connecting and disconnecting the voltage probes, leading to slight changes in conductor geometry. Another source of this variation was identified by carrying out a series of sequential discharges of the system, which all produced slightly varying MIDOT signals for the same experimental configuration. This was put down to minor variations in the source current pulse between successive discharges causing slight shot-to-shot variation.

Considering there is no significant cross talk between adjacent MIDOT sensors, it is possible to make an array consisting of hundreds of sensors to obtain maximum data.

Figure 7.39 shows that the mutual coupling of a MIDOT with the source filament pair falls substantially at ± 2 mm from the sensor location. Therefore to obtain unambiguous data the MIDOT probes were positioned 4 mm apart. The initial array was designed to span over 5 cm (to cover half the width of the transmission line on AMPERE). With each MIDOT separated by 5 mm, this required eleven individual sensors to be installed in the MIDOT array.

Figure 7.45 gives a schematic of the original array design, with pictures of the assembled array shown in figures 7.46 – 7.48.
The 63 µm enamelled copper wires making up both the MIDOT and the source filament pair were positioned into channels machined into a polycarbonate sheet and fixed into position using superglue. All the wires perpendicular to the stripline filaments run in a single, wider channel (figure 7.46) and the loop is completed with the ends being threaded into a PCB board (figure 7.47) where a more substantial connection is made.

11 individual sensor channels

single perpendicular channel for MIDOT loop

Figure 7.46, Machined array template with eleven MIDOT filaments fixed into position.

Figure 7.47, Return path and PCB connections for the MIDOT array.

An image of the full array is shown in figure 7.48.
The MIDOT array is used by positioning it so that one of the MIDOT sensors is located directly above the source filament pair, as illustrated in figure 7.45. The use of an additional insulator sheet to increase the vertical separation is unnecessary as the machined channels are 500 µm deep with an additional 50 µm tape layer to hole the wires down. In this case the total vertical height of the MIDOT is 550 µm above the upper conductor of the source filament pair. Figure 7.49 shows the MIDOT array positioned above the stripline source.

Figure 7.49, MIDOT array positioned above the source filament stripline.
The above array was used to obtain preliminary results; these results are presented in chapter 8, together with the design of and results from the next generation MIDOT array.

### 7.9 Initial high voltage test

A HV shot was carried out on the QUATTRO bank at Loughborough University using MIDOT filaments consistent with the 2D model. It was essential to obtain information at high voltage to gain confidence in the scalability of this technique.

The 2D model had filaments which were ~ 2 mm wide and no more than ~50 µm thick (due to computational limits). The calculated open circuit voltages induced in these filaments are compared to the measured open circuit voltage from the sensor filaments.

Initial experiments used two MIDOT filaments 50 µm thick and 2.5 mm wide (the closest match available to the filament size in the 2D model) and were mounted on a polycarbonate sheet as shown in figure 7.50.

![Figure 7.50, Polycarbonate sheet with two MIDOT probes attached.](image)

The polycarbonate sheet was positioned above the strip line such that one MIDOT is above the edge of the flyer and one is at its centre, to enable the largest difference in induced voltage to be seen (assuming the current changes between the centre and the edge of the flyer). The arrangement is shown in figure 7.51.
Figure 7.51, MIDOT sensors positioned above flyer plate section on QUATTRO.

Figures 7.52 and 7.53 show the stripline (source) current pulse as measured by the tunnel probes and the associated data from the two MIDOT probes.

Figure 7.52, Measured Current pulse on QUATTRO.

Figure 7.53, Induced voltage on the two MIDOT probes during HV discharge.
As seen in figure 7.53, the filament at the edge measures a slightly higher voltage, implying that more current is flowing in that area. These measured signals are then compared to the modelled results and can be used to validate the overall current distribution predicted by the 2D code. Figure 7.54 shows a comparison between the modelled and measured MIDOT voltage at the centre of the stripline.

The modelled results are based on the mutual coupling determined by the computer model and for the geometry used here (rectangular cross sectional filaments of different sizes), the work on the GMD of such filaments derived by Tasker [65] was used to calculate the mutual coupling between the filaments and can be found in the literature [66]. Once the GMD is determined for this arrangement of conductors the induced voltage can be determined.

Figure 7.54, Modelled and measured MIDOT voltage along the centre of the flyer.

Figure 7.54 demonstrates that there is very good agreement between the results from the MIDOT probe and the 2D model. The MIDOT at the edge has similarly good agreement with the model, proving that the current distribution modelled by the filamentary code is accurate. The voltage in each of the MIDOT sensors can only be generated by a limited family of possible current distributions. If the current distribution predicted by the 2D filamentary calculation lies within this range, it demonstrates an initial verification of the model. Future improvements to the
resolution of the MIDOT system will lead to higher order verification of the accuracy of the computer model and therefore present a more reliable picture of the actual current distribution in a stripline.

The results from these experiments were used as a proof of the concept and a further in depth study of this phenomenon has begun with some promising results being obtained. Chapter 8 describes the initial results and further development of the MIDOT array.
Chapter 8

Development of a second generation MIDOT array

To further develop the MIDOT filament work, a new array was designed and built, consisting of 50 individual probes spaced 2 mm apart. This new array is capable of providing better spatial resolution and more experimental data than the original array described in section 7.7.

In this section various terms are used in relation to the probe and the current sources; as defined in table 8.1:

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIDOT filament</td>
<td>The section of the MIDOT loop parallel to and in closest proximity to the source current.</td>
</tr>
<tr>
<td>MIDOT array</td>
<td>Set of 50 probes fixed into the polycarbonate template.</td>
</tr>
<tr>
<td>MIDOT loop</td>
<td>Complete loop of enamelled wire containing a single filament fixed into the machined array and connected to an oscilloscope via a high impedance voltage probe.</td>
</tr>
<tr>
<td>MIDOT current ((I_{MIDOT}))</td>
<td>The current as measured by the MIDOT technique.</td>
</tr>
<tr>
<td>MIDOT setup</td>
<td>Arrangement of MIDOT and stripline analogues.</td>
</tr>
<tr>
<td>Source current</td>
<td>Current flowing in the source filament/stripline.</td>
</tr>
<tr>
<td>Source filament</td>
<td>Single wire or just the upper conductor of the stripline analogue.</td>
</tr>
<tr>
<td>Stripline analogue</td>
<td>Representation of a very thin stripline, by use of discrete pairs of vertically aligned filaments to allow control over the current location.</td>
</tr>
<tr>
<td>MIDOT probe ‘XX’</td>
<td>The ‘XXth’ filament in the MIDOT array</td>
</tr>
<tr>
<td>MIDOT signal</td>
<td>Either the raw voltage or processed (integrated) signal from the MIDOT filament.</td>
</tr>
<tr>
<td>Zero Position</td>
<td>When the MIDOT and Stripline analogues are located directly above each other.</td>
</tr>
</tbody>
</table>

Table 8.1, Definition of various terms used to describe the system.
8.1 New array assembly

An array of 50 MIDOT filaments (the MIDOT array), allows data from across a continuous stripline to be obtained without having to relocate any equipment between shots, thereby ensuring greater consistency. Figure 8.1 shows the machined array with the channels for the enamelled wire clearly identified.

*Figure 8.1, Machined MIDOT template.*

The use of enamelled copper wire ensures that the wires remain electrically isolated whilst being positioned as close together as possible. The wire is placed in the channels and fixed using Cyanoacrylate glue (superglue). Figure 8.2 shows the array with the first few MIDOT filaments positioned in the machined channels.

*Figure 8.2, Array with the first few filaments positioned and fixed into place.*

The MIDOT filaments form complete loops which are terminated at the edge opposite to the probe, with each MIDOT loop terminated at a slightly different lateral position for ease of connection to a PCB board as shown in figure 8.3.
Figure 8.3, Complete MIDOT loops connected to a PCB board for stronger electrical and mechanical connections.

Figure 8.4 shows how the filaments may not all line up parallel to the machined edges of the channels; this is one of the inconsistencies leading to the errors explained later in this chapter.

Figure 8.4, Inconsistent wire installation, leading to errors in positioning.

Initial tests using the completed array included continuity checks on each MIDOT loop and measurement of the DC resistance of each loop. Any broken or short-circuited loops were identified and omitted from further tests, six out of the fifty filaments were found to be unusable and these were labelled and omitted from any further tests.
8.2 Confirming performance of each loop individually

The MIDOT array and stripline analogue (which is comprised of the upper and return conductor of the stripline) were positioned as shown in figure 8.5:

The MIDOT filament and the stripline analogue are parallel, with the longer edges of the MIDOT loop perpendicular to the stripline analogue, as seen in figure 8.5. This ensures that the induced voltage is only due to the MIDOT filaments in the experimental arrangement, which is essential to enable proper analysis of the induced voltage. If a voltage is induced from an incorrectly positioned probe, it will prevent accurate calibration of the MIDOT array.

Initially the Stanford signal generator was connected to a single stripline analogue, with a 50 Ω in-line resistor used to protect the signal generator. A current was passed through the stripline analogue directly below the first probe in the array, and the induced voltage in this probe was measured using a standard high impedance voltage probe and recorded on an oscilloscope with a 1 MΩ input resistance (to ensure the “open circuit” voltage was measured).
Once the signal has been measured, the MIDOT array was moved until the next filament in the MIDOT array was aligned with the stripline analogue. This process was repeated for each of the 50 MIDOT filaments in the array; and is illustrated in figure 8.6.

For the detection of any systematic error in the arrangement, two signals were measured during nominally identical discharges. The high-impedance probe was connected to the ends of the MIDOT loop and the contacts were inter-changed between the two nominally identical discharges, with the results obtained being defined as the positive and negative polarity of the MIDOT probe. The results obtained for one MIDOT filament are shown in figure 8.7.

Equation (8.1) describes the output obtained from the voltage probe in both polarities:
\[ V_{\text{MIDOT}}^{\pm} = \pm M \frac{dI}{dt} + \frac{Q}{C} + \text{(noise)}, \]  

(8.1)

where \( Q \) is the charge on the capacitors, \( C \) is the capacitance of the system, and the noise is assumed to be dominated by operation of the signal generator.

Subtracting the ‘negative’ signal from the ‘positive’ one and dividing the difference by two removes any capacitive components as well as any noise and ringing, and can be easily achieved due to the asymmetrical loading of the MIDOT loop by the probe. The process leads to the cleaner signal shown in figure 8.8. The procedure described is equivalent to using a high impedance differential probe, and can be achieved to a high degree of shot to shot reproducibility.

![Figure 8.8, Processed MIDOT signal from the stripline arrangement.](image)

Integrating the corrected signal of figure 8.8 allows the MIDOT current to be determined, which can be compared to the measured current in the stripline analogue. This allows the mutual inductance of the particular arrangement to be accurately determined. Figure 8.9 shows the integrated signal once it is matched to the measured source current (by dividing by the actual mutual inductance of the probe to the stripline analogue). This is known as the ‘zero position’ mutual inductance.
This is repeated for each MIDOT in the array, the results from each MIDOT filament in the array should be identical, with any variation reflecting discrepancies in the construction of the MIDOT array. The mutual inductance determined for each MIDOT filament is then used to calibrate the array.

8.3 Confirmation of previous results

The results obtained from the initial MIDOT filament design of chapter 7 were confirmed using the new array. The experimental procedure is almost the same as that used in chapter 7; but with the stripline analogue positioned along the central axis of the MIDOT array as shown in figure 8.10.
This arrangement reduces the errors in the experiment by allowing the signal to be measured for both the ‘zero position’ and on either side, without having to physically move the MIDOT array.

The processed MIDOT signal is integrated and compared to the source current, allowing a mutual inductance versus displacement graph to be generated which highlights the sensitivity of this MIDOT array. To model the array performance accurately, the geometry of the experimental arrangement is required and is presented in figure 8.11.

![Cross section of MIDOT assembly (not to scale)](image)

*Figure 8.11, Cross section of MIDOT assembly (not to scale).*

The array performance was modelled and the results overlapped to simulate the presence of adjacent active stripline analogues. The results shown in figures 8.12 – 8.14 provide the performance characteristics of two equal stripline analogues, initially 10 mm apart with the lateral separation first reduced to 5 mm and then to 2 mm. Each figure also shows the mutual inductance between the MIDOT and the stripline for different vertical separations.
Figure 8.12, Mutual inductance of MIDOT filaments positioned 10 mm apart.

Figure 8.12 clearly shows that the mutual inductance falls away quickly from the ‘zero position’ thereby allowing adjacent stripline analogues (10 mm apart) to be easily identified from the location of the induced voltages.

Figure 8.13, MIDOT results with Stripline analogues 5 mm apart.

Figure 8.13 shows that a 5 mm lateral separation of the stripline analogues allows the signals to be easily distinguished, whereas the two signals become harder to distinguish (especially if the machined channel is 500 µm deep) when the two
stripline analogues are 2 mm apart. This lateral separation is set as the limit for this particular MIDOT array and the performance is indicated in figure 8.14.

![Figure 8.14, MIDOT resolution with sources positioned 2 mm apart.](image)

8.4 Initial experimental results

To estimate the errors due to variations in the assembly of the array a cross-section of one of the channels and the wire used in the array is shown in figure 8.15.

![Figure 8.15, Relative size of the machined channel compared to that of the enamelled wire being used.](image)

As seen, the wire is significantly smaller than the channel in the polycarbonate sheet; assuming that the wire stays within the shaded quadrant shown in figure 8.15, there is a possible vertical positional error of ±62.5 µm and a horizontal error of ±125 µm.
These errors are based on the fact that when the wires are positioned into the channels, they are threaded onto the machined channel and pulled taut before being fixed using glue. The time taken for the glue to cure and the inconsistency in the assembly procedure for each MIDOT loop can lead to some of the wires moving slightly or not sitting at the full depth of the channel. In order to obtain an average of the possible errors it is assumed that the wire can be anywhere in the shaded quadrant of figure 8.15.

The errors associated with the positional uncertainties are highlighted in figure 8.16, which shows the modelled and measured mutual inductance at the ‘zero position’ for each MIDOT filament.

![Figure 8.16, Measured mutual inductance with error bars showing experimental errors.](image)

The nominal value for the mutual inductance is calculated to be 59.2 nH, with the error due to the half width of the MIDOT channel being ±4 nH, as shown by the error bars. The error in the height of the MIDOT filament (see figure 8.15) introduces an additional error of ±5 nH, as identified by the green band across figure 8.16. As the vertical height is more difficult to control, the ‘zero position’ mutual inductances which fall within this band are deemed acceptable for these experiments. Figure 8.17 shows the measured deviation from the expected mutual inductance for each of the probes in the array.
Figure 8.17, deviation of mutual inductance from nominal value.

Figure 8.18 shows the actual mutual inductance for each probe. The values obtained are used for calibration purposes, enabling the stripline analogue current to be determined.

Figure 8.18, MIDOT array calibration values.

The value of the ‘zero-position’ mutual inductance for a given MIDOT filament in the array, is used together with the integrated induced voltage (from the same MIDOT
filament) to obtain the magnitude of the current in the stripline analogue directly below it.

### 8.5 Full array performance and consistency tests

These tests utilised the entire width of the array to determine the location of a stripline analogue which was positioned under different sections of the array. This enabled the performance of specific groups of probes as well as the consistency of results across the whole array to be determined. The stripline analogue was sequentially positioned directly below MIDOT filaments 4, 16, 24, 35 and 46. Taking voltage measurements across the array in each of the above cases and processing the data allowed the mutual inductance between the appropriate section of the MIDOT array and stripline analogue to be determined. Figure 8.19 shows the modelled and measured mutual inductance values at the ‘zero position’ for each of the 5 locations and the change in mutual inductance either side of it.

![Figure 8.19, Measured and modelled mutual inductance variation.](image)

Figure 8.19 shows that the measured data is within the identified experimental errors and that all sections of the array provide consistent data. The modelled values have
a nominal peak value of \( \sim 59.2 \text{ nH} \) as indicated by the horizontal dashed line in figure 8.19 however the measured peak values deviate from this due to the non-uniformities in the construction of the array.

As only one MIDOT filament registers a peak signal in each case (figure 8.19), it is clear which MIDOT filament is at the ‘zero position’. This allows the position of the stripline analogue filament to be identified to an accuracy of \( \pm 125 \text{ µm} \), which is the accuracy of positioning the MIDOT filament within the array template of figure 8.15.

Figure 8.18 gives the measured mutual inductance between any given MIDOT filament and the stripline analogue filament at the ‘zero position’, and it is therefore possible to amend the modelled value of the mutual inductance at each identified ‘zero position’ in figure 8.19 to reflect the actual value at that position. Figure 8.20 uses the measured ‘zero position’ mutual inductance values and shows the decay of the mutual inductance either side of the ‘zero position’.

![Figure 8.20](image)

*Figure 8.20, Measured mutual inductance compared to the modified peak modelled values.*
The results in figure 8.20 have a much closer agreement between the modelled and measured values for the peak mutual inductance value at each ‘zero position’.

One feature to note is that the modelled mutual inductance varies symmetrically about the ‘zero position’; whereas in all cases, the measured values display a consistent asymmetry. In figure 8.21 the amended values for each MIDOT probe are overlaid and as can be seen the mutual inductance distribution is symmetrical about the ‘zero position’.

![Mutual Inductance vs Lateral Displacement](image)

*Figure 8.21, Modelled mutual inductance for each MIDOT with peak values amended to consider errors introduced during construction of the array.*

Figure 8.22 shows the comparison of the measured results compared to the ideal model. As seen in every case, there is an asymmetrical distribution about the ‘zero position’.
As the results are predominantly within the known experimental errors the cause of the asymmetry has not been looked at in detail; however due to the regular nature of the discrepancy, it must be caused by a systematic effect. One potential reason for this discrepancy could be to do with the construction and positioning of the array in relation to the stripline analogue.

On the left of the ‘zero position’ MIDOT, the MIDOT loop has to be positioned across the stripline analogue, whereas on the right hand side no wires have to pass across the stripline analogue. This crossing of the wires is one potential source of the discrepancy. The computer model only assumes the effect of the parallel wires and not the longer edges which are assumed to have no effect. Another reason for the discrepancy could be due to the end of the MIDOT array where the loop is attached to a PCB board (figure 8.3). This along with the probe cables can lead to additional induced voltage leading to an asymmetric mutual inductance distribution.

Figure 8.23, shows a schematic identifying the two areas.
These potential sources of error need to be investigated to better understand this effect, one experiment to conduct could be to position two separate arrays one either side of the zero position. This will obtain the necessary data without requiring any wires to cross over the stripline analogue.

As the results are well within the experimental errors, this is not looked at in any more detail as part of this research and the results obtained can be used to determine the current levels.

### 8.6 Effect of adjacent source loops

The effect of two parallel stripline analogues next to one another is assessed by first determining if any (open circuit) voltage is induced in an adjacent stripline analogue due to a pulsed current flowing next to it. The adjacent stripline analogue is then short circuited to monitor any perturbation this has on the current pulse in the active stripline analogue, due to the presence of eddy currents.
Figure 8.24 and figure 8.25 show the schematic arrangements of the two experiments, with the first using a high impedance voltage probe connected to an oscilloscope to measure any induced voltage.

During the discharge through the active stripline analogue, there was no net induced voltage measured across the adjacent stripline, implying that there should be no current flowing through this loop once it is short circuited. For completeness, a short circuit test was also carried out, as shown in figure 8.25.

Using commercially available PCM designed for low currents, it was possible to measure the current flowing through the active stripline as well as any induced current flowing in the short-circuited loop as indicated by figure 8.25.

No measurable current could be detected in the adjacent loop and the source current pulse also remains unaffected; confirming that there is no cross talk between adjacent stripline analogues in the existing configuration. As this effect is due to the cancelling of the induced voltage from the upper and lower stripline conductors, it
results in no net current flow, it is also feasible to assume that any number of stripline analogue filaments can be utilised as independent current sources without any effect on the current pulse.

The voltage pulse provided by the signal generator is shown in figure 8.26. The four independent outputs that are available are all compared in this figure. Although they should ideally be identical there is some variation between them. To obtain the best comparison for multiple source tests the closest matched outputs were used to drive a pair of stripline analogue filaments.

![Figure 8.26, Signal generator 30 V square pulse output](image)

Outputs ‘T0’ and ‘D’ (as labelled on the signal generator) have the most similar voltage pulse and so these two are used for the multiple source filament tests as they allow for a better comparison of the results.

The two outputs were fed into separate stripline analogues which each had an intrinsic 11 Ω resistance plus an additional 50 Ω resistor connected in series. The resulting current pulses are shown in figure 8.27.
The current pulse remains consistent regardless of whether one or two stripline analogues are connected to the signal generator. This is an essential feature for the following experiments, as the current flowing in the stripline analogues musts must be known a priori to enable tests to be conducted to confirm the performance of the MIDOT technique when used with multiple discrete stripline analogues.

### 8.7 Dual source stripline analogue tests

The purpose of these tests was to determine if the MIDOT array was capable of detecting two independent current sources and to determine the effect of moving these sources closer together. Their initial separation was set at 40 mm, which was gradually reduced to determine the resolution limit of the MIDOT array. To achieve this, a number of stripline analogue filaments were fixed to a 2 mm thick insulator to form the multi-filamentary stripline analogue seen in figure 8.28. Each filament in the multi stripline analogue can be connected independently to the signal generator.

The stripline analogues were spaced 5 mm apart, spanning a total width of 9 cm (which required a total of 17 individual stripline analogues). This allowed the source to be ‘moved’ whilst maintaining the consistency of the experimental arrangement and therefore reducing errors.
Figure 8.28, Multi-filament stripline analogue, simulating a board stripline conductor.

The experimental arrangement used, shown in figure 8.29 is almost identical to the schematic diagram shown in figure 8.10 but has two stripline analogues/filaments instead of one.

![Schematic diagram showing two active source stripline analogues positioned below two independent MIDOT filaments in the array.](image)

Figure 8.29, Schematic diagram showing two active source stripline analogues positioned below two independent MIDOT filaments in the array.

As shown in figure 7.38, each MIDOT filament can be used to detect a current flowing up to 2 mm either side of it, i.e. each MIDOT filament is sensitive to a 4 mm strip below it. The 5 mm spacing between the adjacent stripline analogues ensures the adjacent current sources are always a minimum of 5 mm apart and the diameter of the wires used ensures that the location of the current is known accurately.

The induced voltage for one of the ‘zero positon’ probes is shown in figure 8.30;
Using the procedure described in section 8.2 it is possible to obtain a signal which is proportional to the current and which has the capacitive coupling removed, as seen in figure 8.31.

It is clear that a distinct signal can be obtained from a MIDOT filament directly above the stripline analogue (i.e. at the ‘zero position’). To identify the location of the active stripline analogue, the results for every probe in the array are captured. The entire data set is then processed and the traces plotted on common axes.

Figure 8.32 shows a set of 16 processed signals about the area of interest, with a few key traces identified.
Figure 8.32, Snapshot of the results across the MIDOT array.

The largest signal is defined as originating from the ‘zero position’, in this particular case the largest signal is from MIDOT filament 20, and as the probes on either side of this have a much lower signal it is easy to identify the peak signal and consequently identify the location of one of the stripline analogues.

A corresponding set of data were obtained for the second stripline analogue in the dual source experiment; this data (centred about filament 40) is shown in figure 8.33.

Figure 8.33, Results from second stripline analogue.

In figure 8.33, the peak signal is measured by MIDOT number 40, and the signals from the probes either side of this position are much lower. As MIDOT 41 is
damaged there is only one trace for the adjacent probe in figure 8.33, as opposed to the two adjacent traces in figure 8.32.

The data from figure 8.32 and 8.33 show that the two stripline analogues in this arrangement are separated by 40 mm, this method is not very clear and a better way to appreciate the results is to plot the change in the average peak integrated value from each MIDOT probe in the array. This also allows the resolution of the array to be determined more easily.

### 8.8 Determining resolution limit of array

The average peak value of each integrated MIDOT signal is recorded; figure 8.34 shows how the effects of the rising and falling edge can removed. This is achieved by only considering the central 30%-70% of the signal to determine the average.

![Figure 8.34, Average peak value from integrated MIDOT data.](image)

For comparison with the results of figures 8.32 and 8.33, data for the 40 mm separated dual stripline analogue tests is analysed using the alternative method. Data is taken from across the entire array with the peak integrated value from each MIDOT probe shown in figure 8.35. This allows the largest peaks to be easily identified, enabling the location of the stripline analogues to be quickly and unambiguously identified.
As it is known that there are only two discrete source currents in this arrangement it is clear to see from figure 8.35 that these two sources have been detected by MIDOT number 20 and MIDOT number 40, confirming that the two stripline analogues are 40 mm apart, this is a much clearer way of locating the stripline analogue positions compared to the previous section and provides a clear indication of the performance of the array.

Once the two ‘zero position’ MIDOT filaments are located, the mutual inductance for each of these (from figure 8.18) can be used to determine the magnitude of the current flowing in each of the stripline analogues. Figure 8.36 shows the peak signal from MIDOT 20 which has been divided by 50.17 nH (the value for the ‘zero position’ mutual inductance for MIDOT 20 from figure 8.18) and it is compared to the known source current.
Figure 8.36, Comparison of MIDOT and Pearson measurement of current in the first stripline analogue showing very good agreement.

Similarly for MIDOT 40, the signal is divided by 47.2 nH and shown in figure 8.37.

Figure 8.37, Comparison of MIDOT and Pearson measurement of current in the second stripline analogue, the difference is due to experimental errors.

Due to the various errors in construction covered, not all the measurements are as accurate as that shown in figure 8.36. The range of values of the current that can be obtained from the MIDOT technique considering the experimental error to be ±9 nH are shown in figure 8.38 and 8.39:
Figure 8.38, Current trace obtained from MIDOT filament 20 showing error limits.

Figure 8.39, Current traces for MIDOT filament 40 showing error limits.

As seen the current determined from MIDOT filaments 20 and 40 are within the limits of the anticipated experimental errors.
Repeating the process shown for the other stripline analogue separations, allows results for a range of experimental configurations to be obtained, the results are summarised in figures 8.40 – 8.43.

**Figure 8.40, MIDOT peak signals indicating a 20 mm lateral separation of the stripline analogues.**

**Figure 8.41, MIDOT peak signals indicating a 10 mm lateral separation of the stripline analogues.**
As the stripline analogues get closer it becomes more difficult to distinguish them apart. Figure 8.42 shows an example where the signals are just about resolvable.

*Figure 8.42, MIDOT peak signals, identifying two stripline analogues, but not as clearly.*

Looking closer at the results of figure 8.42, it is possible to identify regions where signals from both source filaments combine, making it more difficult to analyse.

*Figure 8.43, MIDOT peak signals indicating a 5 mm lateral separation of the stripline analogues.*
Although it is possible to visibly distinguish the two peaks in figure 8.43, the signals in-between the two are due to a combination from both stripline analogues. It will therefore require some numerical analysis to process and separate the components of the signal to improve the resolution of the MIDOT array.

One way of achieving this could be to process signals so that adjacent MIDOT probes produce alternating positive and negative results, which would enable better signal analysis. It would also prevent adjacent probes from combining and making the identification of the source current more difficult. This technique has not been investigated but is one method of analysing data that can be looked at as part of follow on work.

As seen in figure 8.43, the two peaks are more difficult to resolve and it is determined that for this specific conductor arrangement 5 mm is the smallest stripline analogue separation which can be resolved without any additional signal processing.

Using figures 8.40, 8.41 and 8.43, it is possible to identify the separation and relative location of the two active stripline. Figures 8.44 – 8.46 show the measured current pulse using the MIDOT technique as well as the upper and lower error boundaries.

![Figure 8.44, Measured current flowing with a stripline analogue separation of 20 mm.](image)
For a 10 mm separation the results are shown in figure 8.45:

![Figure 8.45](image)

**Figure 8.45**, Measured current flowing with a stripline analogue separation of 10 mm.

The smallest separation investigated to date is 5 mm, the results for this arrangement are shown in figure 8.46.

![Figure 8.46](image)

*Array was physically moved to obtain the result for MIDOT 17.5*

**Figure 8.46**, Measured current flowing with a stripline analogue separation of 5 mm.
As the MIDOT array has channels milled 2 mm apart, the array had to be physically moved to obtain all the necessary data for this experiment, thereby introducing further errors to the analysis. Also due to the limitations of the present experimental arrangement, stripline analogues closer than this were not investigated.

The results presented above show the ability of the MIDOT array to determine both the location and the value of the current flowing at different locations across the width of the stripline analogue. The next series of tests develops the understanding of the probe further and uses the MIDOT technique in an attempt to measure the artificially created non-uniform current distribution across the width of the stripline analogue by passing current pulses with a different magnitude through adjacent conductors in the stripline analogue.

8.9 Non-equal source current experiments

For the tests described in section 8.7, the current flowing in adjacent filaments was equal. However to determine the ability of this technique to be used as a current distribution sensor, the array needs to be able to detect differences in the localised current across the width of the stripline.

To assess this, different magnitude current pulses were used at different locations across the stripline analogue of figure 8.28. Initially, the resistance of one of the lines was increased by the addition of a 60 Ω in-line resistor between it and the signal generator (bringing the total resistance of the stripline analogue to 121 Ω). This reduced the current to about one-half of the original value, as shown in figure 8.47.
Figure 8.47, The two different current pulses fed into adjacent stripline analogue filaments.

The measured signals are integrated and plotted on a common set of axes (figure 8.48). However as seen previously plotting only the average peak value provides a much clearer determination of the location of the two individual sources, this is particularly true in this case where the integrated traces overlap making the determination of the peak traces ambiguous.

Figure 8.48, Integrated MIDOT signals with unequal currents in adjacent stripline analogue filaments.
Figure 8.48 shows the integrated signals from several locations across the MIDOT array. The peak signal is from the full current and it is clearly identified as the signal from MIDOT 15. It is not clear whether the peak signal from the reduced current is that from MIDOT 25 or 14; this is because the peak signal from the reduced current produces almost the same integrated signal as that from the probe adjacent to the high current stripline analogue filament.

Using the technique described in section 8.8, the peak integrated signals are plotted (figure 8.49), giving an unambiguous identification of the location of the stripline analogue filaments carrying the current.

![Figure 8.49 Integrated MIDOT signals with unequal currents flowing in adjacent Stripline analogue filaments.](image)

It is clear from figure 8.49 that the two stripline analogue filaments are located below MIDOTs 15 and 25, giving a separation of 20 mm between the stripline analogues. It is also evident is that the signal from MIDOT 25 is significantly lower than that from MIDOT 15, implying non-equal currents are flowing in the two stripline analogues. By using the calibration values from figure 8.18, the value of the two current pulses can be determined as shown in figures 8.50 and 8.51.
Figures 8.50 and 8.51 confirm the ability of the MIDOT technique to identify source stripline analogues 2 cm apart, carrying different currents. The combined results are shown in figure 8.52.
Figure 8.52. Measured current for 2 cm source stripline analogue separation.

These tests were repeated with reduced separation (1 cm) and the results are summarised in figures 8.53 and 8.54.

Figure 8.53, Peak integrated MIDOT values for 1 cm stripline analogue separation.
Figure 8.54, Current magnitude, including error limits for 1 cm stripline analogue separation.

The Peak integrated results for the minimum stripline analogue separation (5 mm) is shown in figure 8.55.

Figure 8.55, Peak integrated MIDOT values for 5 mm stripline analogue separation.

The two peak signals are not very easily distinguished and it is much more difficult to identify the location of the two stripline analogues; this is due to the combination of the signals. It is also difficult to obtain an accurate measure of the current as shown
in figures 8.56 and 8.57 with some of the results being significantly different to the known current. Unfortunately these experiments required repositioning of the MIDOT array to obtain all the necessary data (i.e. MIDOT 15.5) which introduced further errors into the system.

![Figure 8.56, Measured current for MIDOT filament 17.](image)

The results for MIDOT 15.5 are significantly beyond the limits of experimental errors (figure 8.57).

![Figure 8.57, Measured current for MIDOT filament 15.5.](image)

To obtain more accurate results for the 5 mm separation a numerical approach will need to be employed which can decouple the contributions from different MIDOT probes allowing the resolution to be improved.

In general the results to date have allowed the identification of the location and magnitude of discrete stripline analogues which form a pseudo-stripline.
8.10 Interpreting results assuming continuous stripline

Using an array of probes mounted above a solid/continuous transmission line as indicated in figure 8.58 enables a relative current distribution to be obtained by plotting the peak current measured by each MIDOT filament.

![Figure 8.58, Schematic of MIDOT array fielded a continuous-solid transmission line.](image)

As indicated above, each MIDOT filament represents a small portion of the whole stripline and as highlighted in section 8.7, the calibration of the array combined with the integrated peak MIDOT signal allows the current at those specific locations to be determined.

Plotting the measured peak current at each MIDOT filament location allows the variation of the current across whole conductor to be determined. In the case of a uniform current distribution, each MIDOT filament registers the same current and fitting an envelope to the data yields a uniform distribution as shown in figure 8.59.

![Figure 8.59, Envelope fitted to MIDOT data showing a uniform current distribution across the stripline.](image)
Should the current be greater near the edges, the two end probes would record a larger current and the envelope fitted to it would be similar to that shown in figure 8.60, which represents a non-uniform current distribution.

![Diagram of non-uniform current distribution across stripline](image1)

*Figure 8.60, Current distribution across stripline.*

Assuming the data from figure 8.48 was obtained from a solid-continuous stripline, and considering the 4 mm sensitivity of each MIDOT filament in the array, the current distribution across the width of such a stripline can be determined by plotting the peak current value from each MIDOT filament and applying an envelope to it as shown in figure 8.61.

![Diagram of current envelope fitted to data](image2)

*Figure 8.61, Current envelope fitted to data from figure 8.48, with sensitivity of each MIDOT indicated.*
To understand how this particular current distribution would look like in relation to the full width of the upper conductor of the transmission line, it is plotted across the full width of the solid transmission line in figure 8.62.

![Figure 8.62, Current distribution envelope across stripline is shown for clarity.](image)

In the continuous stripline configuration each MIDOT filament can represent up to a 4 mm wide strip. Although this can be refined by using better construction techniques and by changing the separation between the go and return paths of the stripline analogue, or the vertical height of the MIDOT above the upper stripline filament. At this stage a robust proof of principle of this technique has been demonstrated.

Any further progress with this technique including the development of appropriate data analysis approaches to separate data from adjacent probes will form part of follow on work.
Chapter 9

Conclusions

A number of areas of work have been successfully completed as part of this research including:

1. The initial development and proof of principle of a novel inductive sensor.
2. The development of a very accurate and reliable 1D model to predict the electrical and mechanical performance of a flyer plate accelerator.
3. The development of a resistivity model which accurately predicts the performance of the EFDR foil.

9.1 Inductive sensor

Operation of the sensor has been demonstrated using a low voltage experimental arrangement. This technique can be scaled up to higher voltages and currents, making it ideal for use in other close-coupled transmission line geometries. In particular, this technique has been developed to be used with high current EM flyer plate accelerators, to determine, at least qualitatively, the variation in the current across the width of the flat, wide conductors. Results from sufficiently separated (further than 4 mm apart) MIDOT sensors can be easily processed, obtaining a relative current magnitude at the sensor locations without the need for complex computer processing, however once the sensors are brought closer together, the data will need to be processed to separate the contributions from different sections of the stripline.

9.1.1 Inductive sensor performance and operation

Experimental results have shown the ability of this technique to locate current filaments to a very high accuracy. For the system built, discrete filaments were located to an accuracy of ±125 µm, based on the accuracy of the position of the
sensor filament in the array. The level of accuracy can be significantly improved by employing more accurate construction techniques when assembling the array.

The sensor can be used in one of two modes:

1. **Model validation mode**

   In which the induced voltage is measured by a number of MIDOT probes positioned at specific lateral locations, a known vertical height above the upper conductor of the stripline. The voltages obtained are then compared to the modelled voltage at the same locations using the 2D model. Agreement between the measured and modelled voltage at all locations simultaneously confirms that the modelled current distribution is accurate and that the model can now be used to simulate other, less well understood experimental configurations.

2. **Direct measurement**

   In this mode, voltage signals from across the entire width of the MIDOT array are measured and then processed. The integrated signals allow the peak current regions to be identified, and the actual current levels at those locations extracted.

**9.1.2 High voltage tests**

A set of tests at high voltage established that the sensor can be used in a high current environment. The proposed technique has been used to validate the results from the 2D filamentary model (model validation mode). Other tests still need to be conducted, where the current across the entire width is measured directly, however these tests will be performed as part of follow on research and did not form part of this PhD.
9.2 Computer model

The 1D model developed is capable of predicting the mechanical acceleration of the flyer and it has been shown to predict reliable experimental results with positional errors of only ±125 µm and a maximum error in the measured ‘zero position’ mutual inductance of ±9 nH.

The immediate development of this model will be to improve the modelling of the acceleration of the flyer plate by taking into account any additional material properties such as stretching or buckling and any other retarding forces on the flyer to provide a more representative force expression.

Following this, the model will be applied to non-planar conductor geometries to impact non-planar targets. To obtain the most accurate prediction of the flyer performance in this configuration it will be necessary to include all the parallel and perpendicular components of the force at each location. If there is a uniform gap between the target and the flyer, with a large radius of curvature this may not present a difficult task and the 1D model may prove suitable.

However once the target – flyer gap varies across the width, it will become necessary to control the current distribution in the conductors to produce a specific force distribution required to achieve a simultaneous impact across the target surface. Both the computer model and the sensor technology will need to be developed further for this to be achieved successfully.

9.3 Empirical model for the EFDR

The development of an empirical model for the heating and explosion of very large area (greater than 300 cm²) aluminium foils (50 µm thick) subjected to large currents has been successfully demonstrated. Certain aspects of the EFDR operation can be looked into further, such as the mechanisms involved in the foil vaporisation etc. As these were not essential in understanding the performance of the EFDR for the present application, they have not been investigated so far.
The performance of the large foils as used in these experiments has not previously been modelled to an accuracy allowing the current levels to be predicted to within 2%! This enables very accurate experiments to be planned and provides good control over the current pulse and consequently control over the force experienced by the flyer plate during its trajectory.

9.4 Future work

9.4.1 Sensor optimisation:

A few areas have been identified where modifications are possible which can improve the performance of the technique;

1. Design of sensor array

For future work, the MIDOT array will need to be constructed to a very high accuracy and alternative construction techniques will need to be employed. The present array was machined and then assembled by hand, introducing many inconsistencies and errors. These can be partially excluded by utilising automated construction techniques.

The new array would need to be constructed so that every MIDOT has the same mutual inductance value at the ‘zero position’; which can be achieved by using techniques such as laser etching onto a PCB board, lithography or other reliable construction techniques to accurately position the sensor filaments.

With a well designed and accurately constructed array, the relative magnitudes of the integrated MIDOT signals will produce signals directly proportional to the rate of change of the current. Each MIDOT sensor will have the same calibration factor for the ‘zero position’, allowing the relative current variation to be obtained directly from the integrated MIDOT signals.
2. Optimised geometry

Changing the separation (lateral and vertical) of the stripline analogue conductors can lead to a more localised signal and/or a higher induced voltage for the same rate of change of the source current. It will be noted that for all the experiments carried out to date, the go and return conductors for each stripline analogue were separated by 2 mm to reflect the geometry of the flyer plate accelerators developed at both AWE and at Loughborough University.

9.4.2 Further use of the sensor

The sensor can be used to monitor the evolution of the current distribution at a known lateral location during the current pulse. By processing the induced voltage from known MIDOT filaments for specific time intervals during the discharge, allows the evolution of the current at that specific location to be established.

9.4.3 Alternative techniques to determine localised current flow

It has been suggested that thermal effects or the motion/force experienced by the flyer could also be used to determine the current distribution. Although all of these effects are directly related to the current distribution, the main drawback of both is that it takes time for them to become noticeable and/or measurable; for example it takes time for the heat to diffuse through to the top surface of the conductor, and it would not be clear exactly where the current flow associated with these effects was located. The benefit of the inductive method is that it is a direct measurement of an instantaneous EM effect which allows for a precise measurement of the location of the current causing the observed effect.

Other measurement techniques such as an array of B-Dots or other magnetic sensors are not sufficiently accurate due to their physical size. To obtain a reasonable signal from a B-Dot, requires either a large area coil or a large number of turns, making it unreliable for location measurements by introducing positioning errors. If only one B-Dot is used, it cannot verify a current distribution, as any
number of current distributions could lead to a specific magnetic field at the given location.

9.4.4 The way forward

The further development of the inductive sensor will be vital for the planning and designing of future experiments. It is therefore proposed that to follow on from the work described in this thesis, a bespoke HV test bed should be constructed and a series of HV tests carried out with the aim of using a MIDOT array to measure the current across the width of a continuous stripline conductor. This will enable both the 2D filamentary model (used to model the flyer plate performance) and the use of the MIDOT technique to be fully validated in a high current discharge regime.

9.4.5 Further uses of EFDR

It is proposed that the explosion of the EFDR can be used to impart the impulse directly to the target surface by having the target in close proximity or in direct contact with the EFDR. To use this as a realistic method to impart a uniform impulse to the large surface area, the vaporisation mechanisms need to be understood fully to ensure this occurs uniformly while no localised hot spots are created.

To aid in the above proposal one area of research which will need to be conducted is to monitor the vaporisation of foils of various sizes with a high speed camera or radiography to determine which factors affect the EFDR performance. Another option is to use radar velocimetry to monitor the post vaporisation behaviour of the EFDR. This technique has the potential to allow the metallic sections to be monitored through the insulating EFDR housing, but more work needs to be done before this technique is optimised for this application.
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Chapter 5


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## Appendix A-H for Thesis

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Appendix A

AMPERE safety systems

This appendix relates to chapters 2.1.5 and covers all the safety systems incorporated into the AMPERE facility.

The AMPERE facility was designed with numerous safety systems in place to minimise the risk of operator injury. The electrical safety and various dump systems incorporated in AMPERE are described below:

1) Primary capacitor dump system

This dumps the energy of all capacitors to earth via the top common plate to earth via 2 x 500 Ω resistors in parallel, by using the Ross relays normally used to isolate the system prior to charging, but can be operated to redirect the energy to earth via a predetermined route whilst isolating the charging systems.

2) Automated gravity dump

Earthed bars are automatically lowered onto a common plate connected to each capacitor before an operator can enter the HV enclosure. These bars are connected to earth via 2 x 50 Ω ceramic resistors in parallel and are easily visible from outside the HV area and automatically make contact with the top plate prior to unlocking the HV enclosure door. Each capacitor is individually connected to earth via its own dump circuit, which is important in case its own fuse has gone open circuit. Figure A.1 shows the gravity dump system in both the open and closed conditions.
Figure A.1, Gravity dump system in the open case (left) and the closed circuit case (right).

The gravity dump system is operated via a series of pulleys and some cord (visible in figure A.1). Although this may seem a crude and lo-tech approach for this safety system, it is much better than having a pneumatic system which could fail in either the open or closed position. In a gravity dump system, the failure is easily visible, the repair will be trivial and most importantly the system will always fail safe.

In the event that an individual capacitor is discharged through the secondary gravity dump circuit, the other capacitors are protected from the discharge by 500 Ω resistors in series with its dump circuit to prevent any energy from transferring to it. Figure A.2 shows how a resistor is connected to a capacitor,
3) Resistive divider bleed circuit

This resistive divider fulfils two purposes, and was designed and built as a chain of resistors with two read off positions. One was set to measure 500 V when its capacitor is fully charged to 40 kV. This connects to a voltage monitoring relay (VMR); which only allows the interlock on the HV cage to be opened if all of the VMR’s indicate a safe voltage on the capacitors, i.e. all the capacitor voltages are below a safe threshold (approximately 1% of full voltage, i.e. 500 V). A second read off was set at a ratio of 1000:1, i.e. at 40 kV a voltage of 40 V was measured. This was connected directly to an array of analogue volt-meters (12 meters are connected, one for each capacitor) which can be observed remotely via a CCTV system to monitor the behaviour of each capacitor independently during charging. Figures A.3 – A.10 show the components which comprise this system.
The divider circuit is connected directly to the VMR circuit, which ensures that all 12 relays must read a safe voltage on the capacitors before the solenoid actuator can be operated. There is also a visual indication of this condition by the illumination of a green LED which is observed remotely.

The VMR box provides power directly to the solenoid lock which can only be operated once a safe voltage is measured on ALL the capacitors.
Figure A.5, Solenoid actuator lock (right) and capacitor discharged indicator (left).

Figure A.6, Array of analogue voltage meters, each meter represents one capacitor.

4) Isolating relays

A pair of HV Ross relays are used during charging, isolating and dumping the stored energy in the bank from the control room. During charging and firing, the dump relay is lowered (opened), to decouple the primary dump resistors from the circuit. Prior to firing the bank, the charging relay is also opened to isolate the charging system from the capacitor bank and to protect the HV power supply against any feedback from the bank.
5) **Hard wired ground wand**

A separate hard ground ("ground stick") provides a very low resistance path to ground. It is used to ensure all components are fully discharged prior to handling, which is standard practice for all HV installations.

6) **Individually fused capacitors**

A significant difference between this bank and previous banks used for EM flyer plate experiments is that each capacitor is connected to the switch via a current limiting fuse. This safety feature is included to ensure that in the event of an internal capacitor failure, the fuse will act to isolate the faulty capacitor and so prevent a catastrophic failure.
7) Capacitor self-discharge

The capacitors have an internal bleed mechanism which will discharge them if left overnight. This is a crucial feature, as in the event of any failure mode the capacitors can and should be left overnight by which time they will have fully discharged. However the bank should still be approached as though it is charged until it has been confirmed to be safe.

All the features outlined above highlight safety considerations involved in the design of AMPERE. There is also a separate search and lock up system (SALUS) which has to be followed whenever the bank is charged to provide a final check that ensures no personnel are left in the HV enclosure or the exclusion zone. If anyone remains inside the HV area or exclusion zone, there are a number of emergency stops which can either be used to prevent the system from being charged or to interrupt the charging sequence and dump the bank. These are located within the high-voltage enclosure, the exclusion zone and also within the control room.
Appendix B

Commissioning the AMPERE facility

This appendix is related to chapter 2.1.8 and covers the commissioning procedure of the AMPERE facility.

Before the facility could be used it had to be commissioned following an agreed set of procedures, although there were no specific criteria it could be benchmarked against. It was decided to commission the bank against the voltage hold off and its ability to effectively dump various levels of stored energy.

It was initially decided to commission ten of the twelve capacitors to 40 kV, and not the full bank of 12, as 10 capacitors were adequate for the initially planned trials. The procedure adopted required the capacitors to be charged and held at the charged voltage for much longer than in any normal operational mode. This tested the integrity of the HV insulation installed on the system. Subsequently the bank was charged and fired into the 1.6 Ω bypass resistor which has been designed to dissipate the total bank energy.

Figure B.1 shows the current traces for different numbers of capacitors, all the shots are charged to 40 kV and as the number of capacitors increase the time constant increases, resulting in a longer discharge. The current in each discharge was measured using a calibrated Rogowski coil.
Figure B.1, Measured current traces for commissioning shots showing the current traces for 3, 5, 6, 7, 8 & 10 capacitors charged to 40 kV.

Figure B.2 below shows one of the commissioning shots compared to the modelled current trace using the values of the system derived in chapter 3. As can be seen there is very good agreement between the model and the experimental result.

Figure B.2, Modelled and measured current trace for 8 capacitor commissioning shot at 40 kV (80 kJ bank energy).

2.1.9 AMPERE Commissioning issues
There were a number of commissioning issues associated with AMPERE, ranging from identifying inadequate components to finding issues with the underlying infrastructure of the building. During the commissioning process many break down and corona discharge events were identified and were used to evolve the final design of AMPERE. Some of the failure modes are explained below:

1) **Isolating relays**

The isolating relays initially installed were rated to 40 kV; however this was 40 kV pulsed and not DC. As a consequence, the relays failed during one of the charging cycles leading to minor damage to the control circuitry. The relays were replaced with more appropriate 60 kV relays (Appendix A), which were rated to take 80 kV pulsed and 60 kV DC voltage.

2) **Corona discharge**

It was found that HV and corona discharge occurred on electrodes near the concrete walls of the HV enclosure; which was unexpected as concrete is an insulator. It was later discovered that the concrete used to build the enclosure had been doped with a conducting substance used for EM shielding for a previous facility erected in the same enclosure. The areas at risk from breakdown and corona emission were insulated and the CCTV system was used to identify where breakdowns were occurring, which were then appropriately insulated.

3) **Resistor failure**

One major failure which occurred during commissioning was the failure of the ceramic resistor, which exploded violently during the 75% full energy commissioning shot. The resistor was designed to take “8 consecutive full bank energy (120kJ) discharges without cooling” (quote from the technical specification sheet of the resistor). However it failed on the first shot at 75% (75 kJ), as shown in figure B.3. Due to the safety systems and exclusion zones implemented on AMPERE there was
no risk to staff due to the failure and the numerous safety systems in place performed as expected.

Figure B.3, Bank commissioning load (bypass resistor) before and after failure during 75% energy test.

After the failure a meeting with the manufacturers of the resistor identified that this particular application required a different assembly process to that of their standard resistors and a new and improved design having the same overall resistance was provided. Figures B.4 and B.5 show the old and new designs.

The original design failed due to one of the discs in the resistor having developed a hot spot which then led to a localised rapid expansion. Due to the discs being compressed together the shockwave generated shattered the other discs which were in contact, leading to the large explosive event witnessed during the shot. The original design only had 2 sections in parallel as shown in figure B.4.

Figure B.4, Original resistor design, 2 parallel paths to divide the current.

To significantly reduce the current flowing in any given disc the new resistor design had 4 parallel paths for the current to flow though as indicated in figure B.5.
Figure B.5a, Improved resistor design, showing distributed current paths.

The improved had aluminium rings between each ceramic disc, which encouraged a more uniform current flow through the ceramic material.

Figure B.5b, clear photo showing actual resistor (approximately 1 m in length).

Once the new resistor was in place the commissioning process was completed successfully and the bank was ready for use. However due the potentially explosive failure mode the new resistor was housed in a reinforced cage on one of the corner walls of the HV enclosure. A system to “bake” the resistor (by passing a steady current through it for a couple of hours each month) was also implemented, as advised by HVR (the resistor manufacturer), to drive out any moisture absorbed over time by the ceramic material.
Appendix C – QUATTRO Safety systems

QUATTRO has been developed with adequate safety systems in place. The following sections give an overview of the main safety features that were installed this Appendix relates to chapter 2.2.3 of the thesis.

1) Optical trigger

To remove any HV danger to the operator, QUATTRO can only be charged and triggered from a separate room, with the only feed through between the two rooms being either fibre optic or independent isolated low voltage signal cables. A bespoke system was also developed to utilise the fibre optics to trigger the rail gap switches. Figure c.1 shows the optical fibre triggering system.

![Optical system used for triggering the switches.](image)

2) Interlocked laboratory

The laboratory can also be interlocked and a strict two-man working rule is enforced whereby the prescribed list of tasks is carried out by one person whilst the other monitors and ensures no one else enters the HV area. Figure C.2 shows the Castell key system.
3) **Damping**

As QUATTRO does not have its own dedicated area, the space is shared with several other experiments. Due to this an EFDR cannot be used due to the potential of damaging other experiments or making the area inaccessible in the event of a failure. The specific damping system used on QUATTRO was shown in chapter 2. This stainless steel section is a non-destructive means of damping the current pulse to the required level.

4) **Dumping**

As with AMPERE and all other pulsed power facilities there is a low-Impedance ground stick as the final safety measure prior to handling the equipment. QUATTRO also uses a pneumatic system to isolate and dump the system remotely (analogous to the electrically operated relays used on AMPERE) Figure C.3 shows the pneumatic relay assembly.
5) **CCTV**

The entire experimental area is monitored from the control room to ensure the system operates as required and checks are made to ensure that no one is in the HV area when the experiment begins. If anything unusual is seen, the system can be dumped and reset remotely, making it safe. The CCTV system (figure C.4) is connected via fibre optics for additional safety.

Figure C.4, CCTV cameras for monitoring QUATTRO experimental area.
APPENDIX D
Derivation resistance and inductance expressions

As shown in chapter 3 (section 3.1.1) the parameters, $\alpha$ and $\omega$ associated with a capacitor discharge can be easily obtained from the measured current trace, since;

$$\alpha^2 = \frac{R^2}{4L^2}$$  \hspace{1cm} (D.1)

and

$$\omega^2 + \alpha^2 = \frac{1}{LC}$$ \hspace{1cm} (D.2)

In practice, the value of inductance in equation (D.2) is the total inductance of the circuit. Since the initial shots were short circuited just after the switch, the inductance included components from the bank and the switch; this configuration is described in figure D.1.

![Figure D.1](image-url)

**Figure D.1**, A schematic circuit diagram when considering only the switch short shots.

It is evident from figure 1 that the inductance of the system comprises the inductance of the $n$ identical parallel capacitor loop(s) forming the bank (which has a total inductance of $\frac{L_{\text{Bank}}}{n}$) and the switch with a value, $L_{\text{Switch}}$. Assuming the inductance of the switch is fixed and the total inductance of the bank depends on the number of capacitors connected in parallel, the following expressions can be generated;
\[ K_1 = \frac{1}{L_{Bank} + L_{Switch}} = (\omega_1^2 + \alpha_1^2) \cdot C_{Cap}, \text{ for } n=1 \]  \hspace{1cm} (D.3)

\[ K_n = \frac{1}{L_{Bank}/n + L_{Switch}} = (\omega_n^2 + \alpha_n^2) \cdot nC_{Cap}, \text{ for } n \geq 1 \]  \hspace{1cm} (D.4)

In these equations, \( C_{Bank} \) is the capacitance of the capacitor bank \( (C_{bank} = n \times C_{Cap}) \), and \( L_{Bank} = L_{Cap}/n \) and \( R_{Bank} = R_{Cap}/n \), where \( K_1 \) and \( K_n \) are the reciprocal total inductances for configurations using 1 and \( n \) capacitors respectively.

Using the known capacitance \( C_{Cap} \), the discharge of one capacitor loop can be compared to that with \( n \) capacitors in parallel. By comparing the data obtained, it is possible to determine the inductance and resistance of each capacitor loop and also that of the switch.

This is achieved as follows:

Inverting the equations (D.3) and (D.4) and subtracting gives an expression for the inductance of the bank:

\[ \frac{1}{(\omega_1^2 + \alpha_1^2) \cdot C_{Cap}} - \frac{1}{(\omega_n^2 + \alpha_n^2) \cdot nC_{Cap}} = \frac{L_{Bank} + L_{Switch} - L_{Switch} - L_{Bank}/n}{n} \]  \hspace{1cm} (D.5)

\[ \frac{1}{(\omega_1^2 + \alpha_1^2) \cdot C_{Cap}} - \frac{1}{(\omega_n^2 + \alpha_n^2) \cdot nC_{Cap}} = \left(1 - \frac{1}{n}\right)L_{Bank} \]  \hspace{1cm} (D.6)

Rearranging the above leads to an expression for the inductance of the capacitor bank;
\[
\frac{1}{K_1} - \frac{1}{K_n} = L_{\text{bank}}
\]

\[
L_{\text{Bank}} = \frac{n(K_n - K_1)}{(n-1)K_nK_1}, \text{ for } n \neq 1
\]  

By substituting this into equation (D.3) an expression for \(L_{\text{Switch}}\) is obtained as:

\[
L_{\text{Switch}} = \frac{nK_1 - K_n}{(n-1)K_nK_1}, \text{ for } n \neq 1
\]

using equation (D.1), similar expressions for the resistance of the capacitor bank and the switch can be obtained.

\[
\alpha = \frac{R}{2L}
\]

\[
\alpha_1 = \frac{R_C + R_S}{2(L_C + L_S)}, \quad 2\alpha_1(L_C + L_S) = R_C + R_S
\]

\[
\alpha_n = \frac{R_C/n + R_S}{2\left(L_C/n + L_S\right)}, \quad 2\alpha_n\left(L_C/n + L_S\right) = \frac{R_C}{n} + R_S
\]

Subtracting equations (D.11) and (D.12) yields:

\[
2\alpha_1(L_C + L_S) - 2\alpha_n\left(L_C/n + L_S\right) = R_C + R_S - \frac{R_C}{n} - R_S
\]
\[2\alpha_1(L_C + L_S) - 2\alpha_n\left(\frac{L_C}{n} + L_S\right) = \left(1 - \frac{1}{n}\right)R_C\]  \hspace{1cm} (D.14)

\[\frac{2\alpha_1}{K_1} - \frac{2\alpha_n}{K_n} = \left(1 - \frac{1}{n}\right)R_C\]  \hspace{1cm} (D.15)

\[R_{\text{Bank}} = \frac{2n(\alpha_1 K_n - \alpha_n K_1)}{(n-1)K_1 K_n}, \text{ for } n \neq 1\]  \hspace{1cm} (D.16)

Substituting equation (D.15) back into equation (D.11) gives us an expression for \(R_S\):

\[R_{\text{Switch}} = \frac{2(\alpha_n nK_1 - \alpha_1 K_n)}{(n-1)K_n K_1}, \text{ for } n \neq 1\]  \hspace{1cm} (D.17)

Using equations (D.8), (D.9), (D.16) and (D.17), enables the inductance and resistance values for both a single capacitor and an \(n\) capacitor setup to be obtained by knowing the capacitance.

The procedure to parameterise the system is to start with the simplest setup so that only the capacitor bank and the switch are included. For the case where \(n = 1\) only the total lumped inductance and resistance can be extracted. By comparing this result with shots using more capacitors connected the resistance and inductance of the switch and bank can be determined independently as the switch values will remain constant, whereas the inductance and resistance of additional parallel loops will vary in a predictable way.
Appendix E

Determining circuit parameters from measured data

This appendix relates to section 3.1.1 of the thesis and described the methods used to obtain circuit parameters using only the measured current trace.

Using standard circuit theory and a current trace as shown in figure E. 1 (a typical current trace from these experiments), the total circuit inductance and resistance for each particular arrangement were determined. The current trace is used to determine the decay constant ($\alpha$) and the angular frequency ($\omega$) of the discharge. As the circuit is altered by moving the shorting block along the transmission line (figure E.1) the current pulse changes, thereby changing the values of $\alpha$ and $\omega$.

Standard expressions including $\alpha$ and $\omega$ for series RCL circuits are:

\[
\omega^2 + \alpha^2 = \frac{1}{LC} \tag{E.1}
\]

\[
\alpha^2 = \frac{R^2}{4L^2} \tag{E.2}
\]

The total inductance of the system can be expressed as having two components, one arising from the capacitor bank (denoted by the subscript “Bank”), which is a total value from the contribution of the individual capacitors and the other from the remaining stripline (denoted by the subscript “Line”). Equation E.1 can then be expressed as:

\[
K_1 = \frac{1}{L_{\text{Bank}} + L_{\text{Line}}} = \left(\omega_1^2 + \alpha_1^2\right) \cdot C_{\text{Cap}}, \tag{E.3}
\]

For the general case when 'n' number of identical capacitor loops are used, the expression becomes;
\[ K_n = \frac{1}{L_{Bank} + \frac{L_{Line}}{n}} = (\omega_n^2 + \alpha_n^2) \cdot nC_{Cap}, \text{ for } n \geq 1 \quad (E.4) \]

where \( K_1 \) and \( K_n \) are the reciprocal total inductances for configurations using 1 and \( n \) capacitors respectively.

Expressions to determine the inductance and resistance of the circuit (with more than one capacitor loop connected) from the directly measured current pulse are shown below (equations E.5 - E.8). Initial tests used the “switch short” (SS) shots (see figure 3.1) where the aluminium block was clamped across the output from the switch creating the shortest possible circuit. These results represent the combination of the capacitor loops and the switch. It is clear that the switch and capacitor bank cannot be separated experimentally, but as shown below, analysis of the data allows the individual values to be obtained.

By determining the resistance and inductance of the of the switch short arrangement, it is then trivial to determine any additional inductance and/or resistance introduced into the system by analysing the change in circuit response.

The inductance and resistance terms shown below are for the inductance and resistance of the switch (subscript “Switch”) and the capacitor bank (subscript “Cap”).

\[ L_{Switch} = \frac{nK_1 - K_n}{(n-1)K_nK_1} \text{ for } n \neq 1 \quad (E.5) \]

\[ L_{Cap} = \frac{n(K_n - K_1)}{(n-1)K_nK_1} \text{ for } n \neq 1 \quad (E.6) \]

\[ R_{Cap} = \frac{2n(\alpha_1K_n - \alpha_nK_1)}{(n-1)K_nK_1} \text{ for } n \neq 1 \quad (E.7) \]


\[ R_{\text{Switch}} = \frac{2(\alpha_n n K_1 - \alpha_1 K_n)}{(n-1)K_n K_1} \text{ for } n \neq 1 \]  

(E.8)

**Manipulating experimental data**

Expressions E.5 - E.8 enable the total inductance and resistance to be obtained using only the measured current, from which the frequency and the exponential decay can be directly determined. In order to obtain the required information the experimental data was analysed as shown below.

Initially the raw data was plotted, with the offsets manually removed to ensure the data starts from the origin. The data was manipulated to obtain the exponential decay of the bank by plotting only the magnitude of the peaks of the oscillating current (both positive and negative) and fitting an exponential curve to these, this is achieved by using the least squares method. The exponential decay of the peaks of the oscillating current pulse should be of the general form for an under damped circuit:

\[ I = I_0 \cdot \exp^{-\alpha t}, \]  

(E.9)

and once a curve is fitted to the data the exponential decay constant (\( \alpha \)) can be obtained. The frequency (\( f \)) can be calculated from the waveform, and the angular frequency (\( \omega \)), which is equal to \( 2\pi f \), immediately follows; see figures E.1 – E.4.
Figure E.1: Measured current trace for a capacitor discharge with a short circuit applied at the output of the switch.

The figure above shows a typical oscillatory discharge for an underdamped RLC circuit. The high frequency part at the beginning is due to the trigger pulse to the rail gap switch and the time it takes for the rail-gap switch to establish a good wide plasma sheet across the width of the rails. This component is noticeable at these low currents however once the charging voltage is increased these oscillations become negligible compared to the current pulse.

The peaks of the discharge (see figure E.2) can be used to obtain the decay constant directly by using a curve fitting algorithm such as least squares regression and applying an exponential curve to it.
Figure E.2, Modulus of the measured current trace to determine the peaks.

Figure E.3: Exponential fit to the measured experimental data.

Figure E.3 shows the curve fitted to the points identified in figure E.2, the points are manually identified and plotted, followed by fitting an exponential curve to the data using the least squares regression method (built in to MS Excel). This allows direct confirmation of the decay constant ($\alpha$).
To obtain the angular frequency, the first period of the discharge is looked at in more detail (figure E.4) and the periodic time is recorded and used to determine the angular frequency ($\omega$).

![Measured current trace with period identified](image)

*Figure E.4, Measured current trace with period identified.*

The high frequency oscillations here are due to pick up from the rail-gap switch trigger and are not important as the level of this noise stays the same even when the current is an order of magnitude higher and so becomes negligible.

**Results from data analysis**

Using the values of $\alpha$, $\omega$ and the relevant total capacitance, the total inductance can be obtained using equation E.1, (which is also the value of $1/K_n$ in equation E.4). Equation E.2 can then be used to determine the corresponding resistance. With the combined switch and capacitor bank values determined it is possible to repeat the analysis for different configurations and to determine the additional inductance and resistance of the various sections as summarised in table E.1.
Using MathCAD to approximate circuit parameter values

A second method that enables the circuit parameters to be determined uses a software package (MathCAD) to manipulate the data and to extract the values.

The raw data was plotted; but instead of extracting the decay constant by fitting a curve to the experimental data, a series of approximations for fast capacitor bank discharges [34] are applied. Easily measureable values from the experimental data are required to determine approximate values for the inductance and resistance of the relevant experimental arrangement. Using these calculated values a typical RLC waveform can be plotted, which is then compared to the experimental data. Minor adjustments can then be made to the approximations to provide a good match between the model and experimental data.

There are two methods of plotting the waveform, one uses equation E.9 and the second is to use MathCAD to solve a set of simultaneous differential equations to determine the oscillatory waveform. Although both yield the same results, the latter is of much more use in the later stages of the research. Both methods are briefly covered in the following two sections.

<table>
<thead>
<tr>
<th>Component</th>
<th>L (nH)</th>
<th>R (mΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Capacitor Loop + switch</td>
<td>1420</td>
<td>53.25</td>
</tr>
<tr>
<td>1 Capacitor Loop</td>
<td>1249</td>
<td>51.09</td>
</tr>
<tr>
<td>Switch</td>
<td>170.8</td>
<td>1.973</td>
</tr>
<tr>
<td>Bridge</td>
<td>83.64</td>
<td>0.264</td>
</tr>
<tr>
<td>Dynamic Resistor</td>
<td>170.9</td>
<td>2.038</td>
</tr>
<tr>
<td>Rest of stripline</td>
<td>76.25</td>
<td>1.103</td>
</tr>
<tr>
<td>Resistor Transmission line</td>
<td>4424</td>
<td>13.27</td>
</tr>
</tbody>
</table>

Table E.1, Resistance and Inductance of sections of the stripline.
Fast capacitor bank discharge approximations

The approximations applied to the fast capacitor bank discharge are given below [34]. The conditions for which these are valid are that the circuit must be under-damped, a condition usually satisfied by most high-current banks. In this case the following approximations can be used:

\[ L = \frac{P^2}{4\pi^2C} \]  \hspace{1cm} (E.10)

\[ R = \frac{2}{\pi} \sqrt{\frac{L}{C}} (F) \]  \hspace{1cm} (E.11)

\[ I_{\text{max}} = \frac{\pi CV_0}{P} (1 + F) \]  \hspace{1cm} (E.12)

\[ F = \frac{|I_2|}{|I_1|} \]  \hspace{1cm} (E.13)

where \( L \) is the inductance, \( P \) is the period, \( C \) is the capacitance and \( R \) is the total resistance of the arrangement. \( V_0 \) is the initial charging voltage, \( I_{\text{max}} \) is the current at which the exponential decay would intersect the \( y \)-axis and \( F \) is the ratio of the magnitudes of the first two peaks (\( I_1 \) and \( I_2 \)) of the discharge. \( C \) and \( V_0 \) are known from the experiment and \( P, I_1 \) and \( I_2 \) are obtained from the experimental data as indicated in figure E.5.
This approximate method is **only** useful for determining the values of the **total** constant parameters of a circuit. To calculate other effects, such as the time varying resistance and inductance, a differential solver **must** be used.

Results from equations (E.10) - (E.13) using the experimental values identified in figure E.5, allow approximate values for the total (constant) inductance and resistance to be determined. These values can then be used together with equations (E.1) and (E.2) to determine the $\alpha$ and $\omega$ values for the experimental arrangement used to obtain the measured data (i.e. figure E.1). Following this the equation for the oscillatory discharge can be calculated and plotted using equations (E.14) and (E.15);

\[
I_0 = \frac{V_0}{\omega L} \tag{E.14}
\]

\[
I(t) = I_0 \cdot exp(-\alpha t) \cdot \sin(\omega \cdot t) \tag{E.15}
\]

The result from equation (E.15) is then compared to the measured data (figure E.1) and analysed, with minor changes made to the calculated inductance and resistance.
until a good match is found between the model and experimental results at various initial conditions.

**Comparison of modelled results to experimental data**

The results from the MathCAD approach are shown below. As can be seen from figure E.6 the initial approximation generally yields very accurate results. Although there is some discrepancy between the phase of the two traces, this can be easily corrected by slightly altering the values for the total inductance and/or the total resistance. These change the period and the magnitude of the current trace respectively and so provide a much better match between experimental and modelled results as evident in figure E.7.

*Figure E.6, Experimental results (red) compared to initial computer model (blue).*
As can be seen in the later stages of figure E.7, the two traces begin to deviate very slightly. As the model used assumes static conditions and neglects any time varying parameters such as resistance (due to Ohmic heating), this effect is not surprising. These discrepancies will become much more significant at higher currents and so must be accounted for in any subsequent modelling.

Further modelling described in chapters 4 and 5 attempts to model the significant time varying features.

**Comparison of Excel and MathCAD methods**

After making measurements on the various experimental configurations, the results obtained are summarised in table E.2. As can be seen the majority of the results obtained are in good agreement for the two approaches described:
<table>
<thead>
<tr>
<th>Component</th>
<th>Excel (curve fitting)</th>
<th>MathCAD (circuit approximations)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L (nH)</td>
<td>R (mΩ)</td>
</tr>
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</tr>
<tr>
<td>Resistor Transmission line</td>
<td>4424</td>
<td>13.27</td>
</tr>
</tbody>
</table>

Table E.2, Comparison of results using both Excel and MathCAD.
Appendix F

Setting up MathCAD Differential Solver for simple RLC circuit

This Appendix shows how the equations in chapter 3.2 are entered into the MathCAD solver as a series of first order equations.

The array shown sets up the differential equation solver with only first order expressions using only the substitutions defined. In the above expressions “r” is the total resistance of the system and “ind” and “cap” are respectively the total inductance and capacitance of the circuit. “v0” is the charging voltage, “y0” represents the current and “y1” the instantaneous charge in the capacitor bank.

The initial values of the terms y0 and y1 are set as shown below, with the current at time zero set to “0” and the charge on the capacitor equal to the capacitance (“cap”) multiplied by the charging voltage (“v0”) using a different array named “y”:

\[
y := \begin{pmatrix} 0 \\ \text{cap} \cdot v0 \end{pmatrix}
\]

The set of equations are represented in a format MathCAD can utilise. For this application the Runge-Kutta adaptive solver is used. The solver is called up by using the following built in function:

\[
z := Rkadapt(A, B, C, D)
\]
where;
A – Initial values
B – Start time
C – End time
D – Name of array containing differential equations to solve

In this particular case the solver is utilised by running the following expression:

\[ z := \text{Rkadapt}(y, 0, \text{tmax}, \text{Np}, D) \]

The start time is always zero for these experiments, and the end time is set separately by defining a variable called ‘\text{tmax}’, a further variable termed ‘\text{Np}’ is also defined to set the number of points to be solved for and finally the set of differential equations that need to be solved are identified, which are contained in the array named ‘\text{D}’.

The above function returns a matrix of results named “z” (although any name can be given to it at this stage). The elements of the matrix have 3 columns, the first being the time (\(z^0\)), the second the current flowing through the system (\(z^1\)) and the third being the instantaneous charge in the capacitors. (\(z^2\)).

The current flowing through the system is shown below.

*Figure F.1, the modelled Oscillatory discharge modelled by the differential solver.*
The current flowing through the system is a damped sinusoidal discharge as shown in figure F.1).

Figure F.2, This shows the charge on the capacitor decaying from the initial value to zero by the end of the discharge.

The charge on the capacitors decays from the initial value \((\text{cap} \times v_0)\) to zero over the course of the discharge.
Appendix G
ElectroMagnetic acceleration force expression

This appendix relates to chapter 5.2.1, it describes the derivation of the EM force generated by the flow of current in the two parallel conductors.

Assuming infinitely long filaments (in the Oz axis) the simplified Biot-Savart law can be used; figure G.1 is a schematic representation showing the magnetic field generated by a wire carrying current (directed out of the page).

![Figure G.1. Schematic representation of a conductor carrying current and an associated magnetic field line.](image)

The law states that the magnitude of the magnetic flux density, perpendicular to the radius vector at a given point (P) is given by:

\[
|B_p| = \frac{\mu_0 I}{2\pi r_p}, \text{ for infinitely long wires} \tag{G.1}
\]

where \(I\) is the current in the wire and \(r_p\) is the radial distance between the wire and the point of interest.
If both the stator (lower conductor) and the flyer are considered to be very thin and long plates of the same width, the 1D model can be used to determine the magnetic field and the forces in this arrangement.

Both plates are considered to be made from a large collection of straight filamentary conductors of width \( dx \) and length \( l \), lying parallel to the Oz axis. With each carrying a uniform surface current density \( J = I/w \), where \( w \) is the width of the conductor (as seen in figure G.2).

Figure G.2, Stripline conductor shown as a collection of discrete filaments each carrying an equal share of the total current.

If each filament in either the upper or lower stripline conductor is carrying a current equivalent to its width multiplied by the surface current density (i.e. \( dI = J.dx \)), each filament will produce a magnetic field which will all combine to form the overall field at any given location. Equation (5.1) is therefore converted to a differential form to reflect this:

\[
\left| dB_p \right| = \frac{\mu_0 J}{2\pi r_p} \, dx
\]  \hspace{1cm} (G.2)

Figure G.3 shows the component of the magnetic field due to a given filament.
Figure G.3, Arrangement for determining the magnetic field at point P due to the current in the highlighted filament.

The x and y components of the magnetic field at point P are:

\[ |dB_x| = |dB_p| \cos \alpha \quad \text{and} \quad |dB_y| = |dB_p| \sin \alpha, \]

where,

\[ \cos \alpha = \frac{y_p}{r_p} \quad \text{and} \quad \sin \alpha = \frac{(x_p-x)}{r_p}. \]

The x-component of the magnetic field is therefore:

\[ |dB_x| = |dB_p| \frac{y_p}{r_p} = \frac{\mu_0 J}{2\pi} \cdot \frac{y_p}{r_p^2} \, dx \quad (G.3) \]

and the y-component is:

\[ |dB_y| = |dB_p| \frac{(x_p-x)}{r_p} = \frac{\mu_0 J}{2\pi} \cdot \frac{(x_p-x)}{r_p^2} \, dx \quad (G.4) \]
Finally the radial distance can be represented in terms of the x and y values where:

\[ r_p = \sqrt{(x_p - x)^2 + y_p^2} \]  (G.5)

Equation (5.5) can be substituted into equations (G.4) and (G.3) to yield:

\[ |dB_x| = \frac{\mu_0 J y_p}{2\pi} \cdot \frac{1}{(x_p-x)^2 + y_p^2} \, dx \]  (G.6)

and similarly for the y component:

\[ |dB_y| = \frac{\mu_0 J}{2\pi} \cdot \frac{(x_p-x)}{(x_p-x)^2 + y_p^2} \, dx \]  (G.7)

Equations (G.6) and (G.7) can be integrated to determine the total magnetic flux density at point P (\( \mathbf{B}_p \)) produced by all the filamentary conductors.

\[ |B_x| = \frac{\mu_0 J y_p}{2\pi} \cdot \int_0^w \frac{1}{(x_p-x)^2 + y_p^2} \, dx \]  (G.8)

\[ |B_y| = \frac{\mu_0 J}{2\pi} \cdot \int_0^w \frac{(x_p-x)}{(x_p-x)^2 + y_p^2} \, dx \]  (G.9)

The standard integrals shown below can be used to evaluate equations (G.8) and (G.9)

\[ \int \frac{1}{b^2+a^2} \, db = \frac{1}{a} \tan^{-1} \left( \frac{b}{a} \right) \]  (G.10)
\[
\int \frac{b}{b^2 + a^2} \, db = \frac{1}{2} \ln |a^2 + b^2|
\]  
(G.11)

The limits of the integration in equations (G.8) and (G.9) cover the whole width of the conductor and range from \(x=0\) to \(x=w\). If the current density \(J\) is replaced by the expression \(I/w\), the expression that determines the magnetic field at point \(P(x_p,y_p)\) becomes:

\[
\left| B_x(x_p,y_p) \right| = \frac{\mu_0 I y_p}{2\pi w} \cdot \frac{1}{y_p} \left[ \tan^{-1} \left( \frac{x_p-w}{y_p} \right) - \tan^{-1} \left( \frac{x_p}{y_p} \right) \right]
\]  
(G.12)

\[
\left| B_y(x_p,y_p) \right| = \frac{\mu_0 I}{2\pi w} \cdot \frac{1}{2} \left[ \ln \left( |y_p^2 + (x_p - w)^2| \right) - \ln \left( |y_p^2 + x_p^2| \right) \right]
\]  
(G.13)

Equation G.13 can be reduced to

\[
\left| B_y(x_p,y_p) \right| = \frac{\mu_0 I}{4\pi w} \cdot \ln \left( \frac{y_p^2 + (x_p-w)^2}{x_p^2 + y_p^2} \right)
\]  
(G.14)

The force on the flyer filament (with a current density \(J\)) due to the magnetic field \(B\) generated by the stator is calculated using the standard expression:

\[
F = J \times B
\]  
(G.15)

In the case of the filamentary representation, each filament generates a component contributing to the overall force. The differential force is obtained by taking the cross product of the current density \((I/w)\) in the flyer with the magnetic field produced by the corresponding filament in the stator for a given filament of width \(dx\) leading to equation (G.16).

\[
dF = \frac{I}{w} \times B \cdot dx
\]  
(G.16)

As the current is flowing in the direction of \(\hat{I}\); equation (5.16 can be written as:
\[ dF = \frac{1}{w} (l \times B) \cdot dx \quad (G.17) \]

The cross product produces a force containing two components, achieved by taking the determinant of the matrix shown below (G.18):

\[
dF = \frac{Idx}{w} \begin{vmatrix} k_x & k_y & k_z \\ 0 & 0 & -1 \\ B_x & B_y & 0 \end{vmatrix} = \frac{Idx}{w} \left( B_y k_x - B_x k_y \right) \quad (G.18)
\]

There is thus a component of force in both the x and the y directions, with the force in the y-direction due to the x-component of the magnetic field and vice versa in the x-direction.

Considering all the filaments making up the conductor (figure G.3), it is clear that the forces in the x direction cancel (when integrated across the whole width). By comparison, the vertical force components combine, to push the upper and lower conductors apart. It is therefore only the y-component of the force which needs to be considered for the 1D model being developed, and so \(|dF_y|\) can now be expressed as:

\[
|dF_y| \bigg|_{y=d} = -\frac{l}{w} B_x(x, d) dx = -\frac{\mu_0 l^2}{2\pi w^2} \left[ tan^{-1} \left( \frac{x-w}{d} \right) - tan^{-1} \left( \frac{x}{d} \right) \right] dx \quad (G.19)
\]

where \(x\) is the position of the filament in the flyer foil. The differential force obtained from equation (G.19) is responsible for the vertical acceleration of the flyer, and is used in the computer model. The total accelerating force \(|F_y|\), acting on the flyer at a distance \(y = d\) from the stator is:

\[
|F_y(d)| = \int_0^w |dF_y| dx = \frac{\mu_0 l^2}{2\pi w^2} \left[ 2wtan^{-1} \left( \frac{w}{d} \right) - d \ln \left( \frac{d^2+w^2}{a^2} \right) \right], \quad (G.20)
\]
where $d$ is the separation between the flyer and the stator.

Equation (G.20) is an accurate formula for the total force as it incorporates the separation of the conductors rather than using the magnetic pressure to estimate the force as used in the past. Equation (G.21) [53] shows the expression used to determine the forces from the magnetic pressure.

$$|F_y| = \frac{(2B^2)}{2\mu_0} l w = \frac{(2\mu_0 \frac{l}{2w})^2}{2\mu_0} l w = \mu_0 \frac{l^2 l}{2w},$$  

(G.21)

from which it is clear that the force calculated using the magnetic pressure is independent of the separation of the flyer and stator and so remains constant (for a constant current) during acceleration.
Appendix H –
Review of Pre-existing diagnostic techniques

The work presented in this thesis utilised many standard diagnostics such as voltage probes and current monitors (Rogowski coils and Pearson current monitors), as well as a range of more specialised diagnostics such as high-speed photography, in-situ inductive current monitors, interferometric diagnostics and carbon pressure gauges, together with CCTV systems to monitor the experimental area. The diagnostics are briefly covered in chapter 6 with the benefits of the various techniques being highlighted.

Both current measuring devices used are standard commercial items; one was developed by Pearson electronics Inc. Model number 2093; calibrated to operate to a maximum current rating of 500 kA, and the other by PEM UK (Power Electronic Measurements Ltd) and custom built to have a maximum current rating of 600kA.

Figures H.1 and H.2 show a comparison between the outputs of the two current measuring systems that were used, and as can be seen they provide equivalent results.

![Figure H.1, Pearson current monitor (dashed) and Rogowski coil (solid) current measurements for the same discharge.](image-url)
A closer look at the rising edge highlights the difference between the two devices.

The Pearson current monitor (PCM) produces a much cleaner signal as it is well shielded, whereas the Rogowski coil (RC) is susceptible to electrical noise from the experimental arrangement. Figure H.3 and H.4 show the actual locations where the probes were installed on the experimental assembly.

The PCM has a fixed location within the experimental arrangement and cannot be easily moved due to its physical size. The Rogowski coil however, is designed to be easy to move and install around various conductors, this is possible due to its light weight and physical design as can be seen in figure H.3.
Figure H.3, Open Rogowski coil positioned around upper conductor of stripline (Left), Rogowski coil fully closed and secured (Right).

The Pearson current monitor is placed on the return conductor below the rail-gap switch as indicated in figure H.4.

Figure H.4, Position identified for locating the Pearson current monitor.

A second Rogowski coil was used to measure the current flowing through the parallel resistor, positioned as shown in figures 2.1 and 3.1 in chapters 2 and 3. This current was used as a means of validating the computer model as well as providing a record of the current flowing through the resistor. The measured and modelled current in the parallel path as well as the EFDR are shown in figures H.5 and H.H.
Figure H.5, Current flowing through the stripline and the parallel resistor path.

Figure H.5 shows the current discharge for a 31 kV charging voltage which uses a 10.8 cm wide, 30 cm long EFDR. The current in both paths is shown in the above figure.

The PCM measures the current in the stripline and the RC measures the current in the resistor. Figure H.6 shows a closer view of the current in the parallel resistor path.

Figure H.6, Current flowing in the parallel resistor path for the same shot as in figure H.5.

The ringing observed in the measured Rogowski data is due to the operation of the rail gap switch. As the current measured is very low, this ringing seems to dominate
at the beginning of figure H.6; comparing this data to that in figure H.1 shows that the ringing does not increase at higher currents and so can be attributed to the noise generated by triggering the switch.

The agreement between the modelled and the measured current traces especially in the parallel resistor path confirms that the EFDR is being modelled accurately.

**Rogowski coil**

A Rogowski coil enables monitoring of transient current pulses. The pulsed current in the conductor generates a transient magnetic field; which gives rise to an induced voltage in the RC proportional to the rate-of-change of the current being measured. The induced voltage needs to be integrated to provide useful results. The signal can be integrated by either a separate passive (a simple resistor-capacitor network) or an active integrator which uses an op-amp to generate a larger signal. Figure H.7 shows a diagram of a RC being used.

![Rogowski coil schematic diagram](image)

*Figure H.7 Rogowski coil schematic diagram.*
A RC is an open ended loop which enables it to be positioned around any conductor of interest as shown in figure H.7. The RC used on AMPERE (figure H.3) was specifically designed by Power Electronic Measurements Ltd (PEM) [56], and was specified as being able to measure peak currents up to 600 kA with a rise time of \(~10 \mu s\). It was calibrated for use with 30 m of additional cable (of specified properties) to ensure the signal could be fed into the screened room.

Using a Rogowski coil to measure fast transient currents has many advantages over other methods of current measurement:

- The RC is very easy to install on any existing system with accessible conductors.
- It is possible to have varying coil sizes, ranging from a few mm up to tens of metres in diameter.
- It presents only a few pH of inductance to the circuit under test and does not affect the circuit performance.
- RCs have a large bandwidth and can be used in a wide variety of situations.
- There is good linearity/scaling to larger currents; the only consideration is to ensure that adequate insulation is used to prevent a HV breakdown.
- RCs can tolerate a large over-current (as specified by the manufacturer) without damage.
- The integrator circuit allows a signal directly proportional to the current to be obtained. The integrator can be a passive or an active device.

**Pearson current monitor (PCM)**

The main difference between the PCM and RCs is that the PCM has a closed loop around a ferrite core. As such it is not usually possible to have an open ended PCM and so it is a more permanent installation.

Figure H.8 shows the schematic diagram of a PCM used in a single conductor/bus bar configuration. The primary winding is the main conductor carrying the current to be measured and passes through the centre of the PCM (this can be thought of as a
single-turn primary in a standard transformer configuration). The ferrite core acts to concentrate the magnetic field generated by the alternating current and as the coil is wound around this core, the induced voltage in the secondary is enhanced, leading to a better signal to noise ratio.

![Schematic representation of Pearson current monitor.](image)

*Figure H.8, Schematic representation of Pearson current monitor.*

Just as with RCs, this system ensures no physical contact is required with the HV conductors, which makes it safer and less invasive than other direct measurement techniques such as in-line ammeters. Also by controlling the ratio of the number of primary to secondary turns it is possible to obtain a large signal to noise ratio.

A PCM should not be used above its specified current-time integral, as above this limit the ferrite core saturates and the induced voltage is no longer directly proportional to the current in the primary conductor. In the case of AMPERE the PCM is only safe to a peak current of 500 kA, and if this is exceeded, the PCM must be removed to ensure it is not damaged.

Both the RC and the PCM are suitable for use on AMPERE and provided the results shown in figures H.5 and H.8. Unfortunately on QUATTRO the entire system was constructed to minimise inductance and all the conductors are very closely coupled and made of wide sheets of copper. Due to this there is no suitable place to install either a PCM or a RC without affecting the performance of the bank. To overcome
this, a different non-invasive probe was developed and installed as part of the lower stripline, as described in section H.4.

**In-situ current monitor (Tunnel probe)**

To obtain accurate current measurements, a special purpose current monitor was developed. This was designed to be positioned within the lower conductor of the stripline, within a ‘tunnel’ as shown in figure H.9. This ensured there were no adverse effects on the electrical performance of the system.

Two separate probes were built and installed perpendicular to the current flow (one from either side of the transmission line) to allow the EM noise to be removed from the measurements and to provide more confidence in the results.

*Figure H.9, “Tunnel” soldered to the lower conductor of the stripline, upper conductor is not shown for clarity.*

The current flow in figure H.9 is from right to left and around the tunnel in a clockwise direction. The tunnel causes negligible change to the inductance of the stripline, and to prevent breakdown across the opening at the top it is lined with Mylar as shown in figure H.10.
Figure H.10, Lower conductor tunnel lined with Mylar to prevent electrical breakdown.

The introduction of this tunnel creates a conducting loop which can be thought of as a solenoid. As the magnetic field inside the loop is due to the total current in the conductor, it enables a measurement of the total current to be obtained even if the current is not uniformly distributed across the width of the lower conductor. By considering the magnetic field at the centre of this solenoid, the tunnel probes can be designed, built and calibrated.

**Tunnel probe construction**

The probe mounted in the tunnel is made from a 50 Ω co-axial cable with the sheath and braiding stripped back by 35 cm, being half the width of the stripline. The exposed inner core is used as a mandrel onto which a coil of 0.5 mm enamelled wire is wound (figure H.11).

Figure H.11, Diagram of a current monitoring probe as used on QUATTRO.
Tunnel probe theory

Using data generated from the QUATTRO bank (in its previous configuration; the system inductance was assessed as approximately 40 nH. Assuming a maximum charging voltage of 20 kV, the greatest rate of change of current can be predicted and used to model the performance of the probe.

An output signal of a few hundred volts is required from the probe to ensure background noise does not affect the readings. Using equation H.1 and the geometry of the probe, the voltage output is:

\[ V_{out} = N \cdot \frac{dB}{dt} \cdot Area_{loop}. \]  

(H.1)

where \( N \) is the number of turns in the solenoid, \( Area_{loop} \) is the cross sectional area of the loop and \( \frac{dB}{dt} \) is the rate of change of the magnetic flux density. For a solenoid as shown in figure H.12, carrying a current \( I \), the magnetic flux density on the central axis is:

\[ B = \frac{\mu_0 N I}{2l} \left[ \frac{x_2}{\sqrt{x_2^2 + r^2}} - \frac{x_1}{\sqrt{x_1^2 + r^2}} \right] \]  

(H.2)

where \( I \) is the current, \( l \) is the length of the probe, \( x_1 \) and \( x_2 \) are the lengths from either end of the solenoid and \( r \) is the radius of the probe (including the wire diameters). For simplicity the solenoid turns are shown with a square cross section:
Figure H.12, Diagram showing centre line section through a solenoid.

For simplicity the field is calculated at the centre of the solenoid (when \( x_1 = -x_2 = l/2 \)), which reduces equation (H.2) to:

\[
B = \frac{\mu_0 IN}{\sqrt{l^2 + 4r^2}},
\]  

(H.3)

and as the magnetic flux density is proportional to the current, where the \( K \) factor is determined by comparison to a pre calibrated device (such as a pearson current monitor). Determination of the \( K \) factor is outlined in figure H.19 and figure H.20.

\[
\frac{dB_{\text{max}}}{dt} = K \cdot \frac{di_{\text{max}}}{dt}.
\]  

(H.4)

The maximum rate-of-change of current occurs at the time of switching i.e. at time zero, and this can be determined from the initial conditions of the bank. Since the inductance is \(~40\) nH and the maximum charging voltage of QUATTRO is 20 kV, the maximum rate-of-change of current is:

\[
\frac{di_{\text{max}}}{dt} = \frac{V_0}{L_{\text{system}}} = \frac{20000}{40 \times 10^{-9}} = 5 \times 10^{11} \text{ A/s}
\]

In this arrangement, \( l \) is 35 cm and \( r \) is 1.5 mm, these values are obtained from direct measurement of the probe. Rearranging equation (H.1) for \( N \), replacing with equation \( \frac{dB}{dt} \) (H.4), and using the physical dimensions of the probe enables the
number of turns required to provide a specified peak $emf$ to be calculated.

To obtain a peak 100 V signal from the probe with the bank charged to 20 kV, 20 turns need to be wound onto the mandrel. Two nominally identical probes were constructed. Due to variations during the assembly, each probe recorded a different voltage for the same current flowing through the stripline conductor. To resolve this issue the probes were independently calibrated prior to their use.

**Installing and calibrating tunnel probes**

Figure H.13 indicates the relative position of the two probes with respect to the lower stripline conductor;

![Diagram of two tunnel probes installed within the lower conductor of the stripline on QUATTRO.](image)

*Figure H.13, Two tunnel probes installed within the lower conductor of the stripline on QUATTRO.*

Due to the probes being installed in opposite directions it is possible to process the data and remove the common system noise. Figure H.14 shows the unprocessed data from the two probes.
The data from the two probes are compared as shown in figure H.15:

To calibrate the probes, QUATTRO’s load was changed from a parallel plate flyer to a thick copper wire which was passed through a PCM (figure H.16).

Obtaining agreement between both tunnel probes and the PCM for this configuration allowed the tunnel probes to be accurately calibrated.
The data in figure H.14 is integrated to yield a signal proportional to the current. Figure H.17 shows the first half period of the discharge; the difference between the two signals is due to the variations in the construction of the probes:

![Graph showing integrated signals from two probes.](image)

*Figure H.17, Integrated signals from the two probes, (they should be the same the differences are due to errors in construction).*

The signals are corrected by introducing factors to each measured signal to ensure they produce identical results for the same current pulse. As an additional test, the two probes were then interchanged and the tests repeated; using the correction factors identified for each sensor the results obtained are shown in figure H.18.
Figure H.18, Identical traces from both probes after calibration.

Figure H.19 shows the signals from the two tunnel probes compared to the current measured by the Pearson current monitor.

The results from the tunnel probes are adjusted (to identify the ‘\(K\)’ factor in equation (H.4), which enables the integrated probe data to be equated to the calibrated PCM data as shown in figure H.20.
The tunnel probes have been shown to produce results equivalent to a calibrated PCM. The PCM can therefore be removed and the stripline returned to its original low inductance configuration. The calibrated pair of tunnel probes can be used to measure all future discharges on this bank with confidence.

**Laser diagnostics – Interferometry**

Interferometry is based on the interference of two beams of light coming from the same source, but traveling along different optical paths. Usually one beam is reflected off a stationary surface (the reference beam) and the other off a moving surface.

Interference between the two coherent laser beams is used to determine the motion of a reflective surface. In this particular case there are two specific configurations of this technique which have been used; one to measure the large displacement of the flyer plate itself and the other to monitor the much smaller perturbations of the front and rear surface of the target upon impact. Motion of the flyer plate is monitored by a technique referred to as PDV (Photon Doppler Velocimetry), whereas the target surface (the side facing away from the incoming flyer plate) is monitored using a technique called PDI (Phase Doppler Interferometry). PDI is more sensitive and is capable of determining the minute motion of the rear surface during the impact;
however this technique requires more precise focussing and is only useful for a small range of motion.

Both techniques utilise the same physical equipment but in slightly different configurations. The more sensitive PDI arrangement also requires data to be collected on three separate channels of an oscilloscope. The system implemented on these experiments was developed at AWE [57]; however details of various interferometry techniques can be readily found on line [58].

The laser interferometry diagnostics used in these experiments have been previously tested and calibrated on other facilities in both the UK and in the US [59]. The basic principles are the same as that of a Michelson interferometer which is outlined in figure H.21, details of this technique can be found freely in literature.

![Figure H.21, Schematic of a simple Michelson interferometer.](image)

The Michelson interferometer uses a beam splitter to divide and recombine the beams. To keep the optical paths constant, compensation plates are added to
ensure both beams travel through the same materials an equal number of times, and as the beams combine, they produce an interference pattern on the screen. The fringes which are created respond to movement of the reflecting surface, with the movement of one fringe corresponding to a displacement of the moving surface equal to one wavelength of the light being used. This allows either the wavelength of the light or the displacement of the reflective surface to be accurately measured.

Figure H.22 shows a more representative diagram of the actual arrangement used in the experiments on AMPERE.

![Figure H.22, Arrangement of the PDI technique used in the flyer plate experiments.](image)

The data obtained form the PDI technique [60] can be processed to determine the velocity of the moving surface (as shown in figure H.23) and can also determine the direction of the motion, which is not usually possible with a standard interferometer (which relies only on path lengths). The data shown in figure H.23 was obtained from available literature [61].
High speed photography

In order to validate the velocity data from the laser diagnostics, a direct measurement of the velocity of the flyer plate was required, with the most reliable method being the use of a high-speed photography system.

Two different optical imaging arrangements are shown below, the first (shown in figure H.24) provides a general view of the experimental arrangement and establishes the best triggering systems and optical alignments etc. The second (shown in figure H.27) aims to capture the most useful field of view (FOV) of the experiment.

An ultrafast framing camera with a frame rate of up to 500 million frames per second (fps) was used, which was capable of capturing eight individual images (frames) triggered at precise moments. The captured images, together with the inter-frame timings, allow the velocity data to be determined very accurately. The camera system was constructed and operated by the diagnostics team at AWE.
Figure H.24, Schematic layout of proposed equipment layout for high speed camera diagnostic.

Figure H.25 shows the actual diagnostic equipment installed on the AMPERE facility. In order to obtain usable images adequate pulsed flash lighting was essential and provided as seen in figure H.25.

Figure H.25, Optical alignment of camera and mirrors and also the flash-lamps and object lens.
The camera in figure H.25 is placed ~5 m away from the object to ensure that electrical noise does not pose any threat to the sensitive electronics of the control and image capture circuits. The various lenses and mirror arrangements allow a FOV of 7.5 mm x 7.5 mm to be captured.

The results obtained from the initial test are shown in figure H.26 as a series of images, with the flyer and target edges highlighted to indicate the motion of the flyer relative to the target at various times during the discharge. These shots were used to determine the most suitable triggering and optical arrangements required to obtain the best data.

Figure H.26, Summary of flyer motion.

The subsequent shot used a technique known as “anamorphic lensing” to obtain a different FOV, which could encompass much more of the width of the flyer and still focus on a relatively narrow height. For this arrangement the camera was moved closer to the experiment (positioned at ~3 m) and two different, mutually orthogonal
cylindrical lenses were used to focus on the region of interest. The objet lens used in the initial arrangement has been removed as evident in figure H.27.

Figure H.27, Anamorphic lensing arrangement to obtain a more useful FOV.

The actual experimental assembly is shown in figure H.28.

Figure H.28, Final arrangement of “Ultra 2” camera, used to obtain the 5 mm x 50 mm FOV necessary to analyse the flyer motion.
The FOV obtained is shown in figure H.29. The blue line is the edge of the flyer (after being covered in blue tape), the grid which can be seen is held behind the target front surface to provide some fiducial markers for post-shot analysis. As indicated an aspect ratio of 1:10 was achieved which would not have been possible using standard lenses.

![Image of FOV obtained using anamorphic lensing](image)

**Figure H.29, FOV obtained using anamorphic lensing, allowing area of interest to be viewed.**

The final arrangement had a FOV which was 3 mm high and 30 mm wide. This allowed much more information about the planarity of the flyer to be obtained from the results as shown in figure H.30:

![Images of flyer motion](images)

**Figure H.30, Motion of the flyer seen over a FOV 5 mm x 50 mm.**
The new FOV allows the planarity to be observed over a larger width of the flyer. The results from the high speed photography are used to verify the laser diagnostics. The laser diagnostic has numerous advantages over high speed photography; firstly it is much easier to install, and it also allows data from across the entire flyer area to be obtained. This provides 2D information, whereas the photographic method can only monitor a single edge of the flyer for any given shot.

**Carbon pressure gauge**

A major drawback of the laser diagnostic is that it cannot monitor the front surface pressure pulse on opaque targets, which is of concern as most materials of interest will be opaque. To overcome this, carbon pressure gauges can be used. These are a form of piezo-resistive device in which the applied pressure is determined by monitoring the change in resistivity during the impact. This is determined by applying a known voltage pulse and monitoring the current through the pressure gauge during the impact.

The gauges used here are made by Dynasen and have a $50 \, \Omega$ strip-type design [62] as shown in figure H.31:

![Figure H.31, Sandwich structure of the Dynasen pressure probe [62].](image)

The construction of the gauge is a simple copper stripline, separated by a thin insulating layer which is all encased in Kapton. One of the probes used is shown in
figure H.32 installed on a clear target to provide a comparison between the laser diagnostics and the pressure gauge.

![Diagram of Dynasen Carbon gauge installed onto the front surface of a clear target.](image)

*Figure H.32, Dynasen Carbon gauge installed onto the front surface (side being impacted) of a clear target.*

In figure H.32, the thin black section is a layer of deposited carbon and forms the active part of the strain gauge. Monitoring the change in the resistivity of the gauge during the impact allows the applied pressure to be determined.

The optical diagnostics used on the AMPERE experiments were not available when a similar series of tests were carried out in the 70s and 80s. These previous facilities relied on the carbon gauge and so there is the possibility of read across from old test data if carbon gauges are used, allowing the present tests to be compared to those conducted in the past. An additional benefit of using the carbon gauge is that it can be positioned on any part of the target, as long as it is adequately screened from electrical noise and insulated from the current generated by the experiment, as seen in figure H.33.

![Diagram of Carbon gauge with aluminium foil used to shield electrical noise.](image)

*Figure H.33, Carbon gauge with aluminium foil used to shield electrical noise.*
Figure H.34 shows the Dynasen gauge installed along with 3 optical laser interferometry probes on the same shot. This was used to verify the results from the carbon gauge.

The input signal used to determine the pressure is given in figure H.35, with the flat top of the pulse used as a reference to enable the change in resistance to be determined by monitoring its change upon impact.

To use the carbon gauge successfully the voltage pulse must be timed to coincide with the anticipated impact time of the flyer. Figure H.36 shows the input pulse as
well as the effect due to the impact; superimposed on the original trace the change in voltage can be correlated to a change in resistance which is used to determine the applied pressure.

Figure H.36, Original input pulse and effect of flyer impact on strain gauge voltage.

The effect of the impact on the carbon gauge is short lived and so a very short period is monitored as seen by the red part of the trace in figure H.3H. The data obtained can be used to directly determine the pressure applied to the gauge.

The carbon gauge, whilst providing useful data is extremely sensitive to EM noise and so is not ideal for use in a high current environment; however it is currently the only method to measure the front surface pressure pulse applied to opaque targets.